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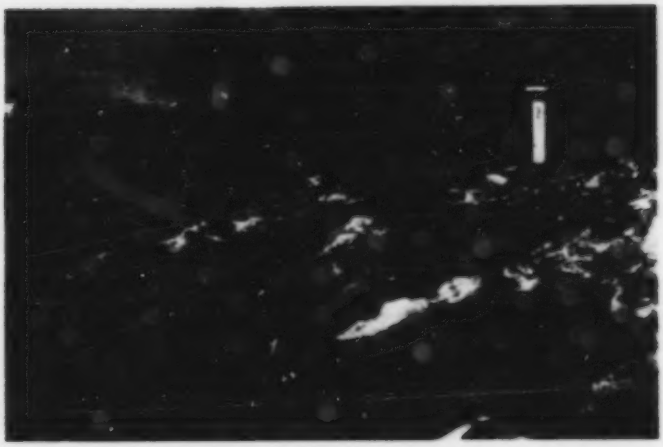
WORKING GROUP ON RIVER ICE JAMS



FIELD STUDIES AND RESEARCH NEEDS

S. Beltaos, R. Gerard, S. Petryk, T.D. Prowse

National Hydrology Research Institute
Science Report Series

NHRI Science Report No. 2

National Hydrology Research Institute
Environment Canada
Saskatoon, Saskatchewan
S7N 3H5

1990

Cat. EN36-513/2E
NHRI Science Report No. 2

ISSN 0838-9052
ISBN 0-662-17566-2

FOREWORD

The Working Group on River Ice Jams was formed in 1982 under the auspices of the Subcommittee on Hydraulics of Ice-Covered Rivers, in turn affiliated with the Associate Committee on Hydrology of the National Research Council of Canada. Its membership was as follows:

S. Beltaos (Chairman), National Water Research Institute
D. Andres (Secretary), Alberta Research Council
B. Burrell, Environment New Brunswick
R. Gerard, University of Alberta
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Ice jamming causes serious problems and damage along Canada's rivers, but there exists little hydrotechnical knowledge to enable efficient and reliable ice jam management. The most pressing need perceived by the Working Group upon its inception was to promote development of meaningful research and data collection programs. As a result, the following four tasks were defined:

1. To develop guidelines for needed data collection programs. Improvement of present knowledge depends to a large extent on accumulation of pertinent field data but progress is hampered by lack of concrete guidelines on the kind of data that should be collected and why.

2. To develop guidelines for analyzing data that are already available. This mainly refers to existing records associated with the national network of hydrometric gauges operated by the Water Survey of Canada and other agencies. Such records are far from ideal for studying ice effects, but useful (and inexpensive) information can be extracted from them.

3. To identify research needs. Identification and rationalization of important areas of study is a vital step toward creating new knowledge, especially on a subject as little understood as ice jamming.

4. To promote the documentation and publication of design-performance case studies. On many rivers experiencing ice-jam problems, engineering studies have been carried out by entities concerned with planning, design, construction and operation of river development projects. This collection of case studies would include an outline of the ice-jam related work carried out, in

progress or planned, and would identify reference documents and contact person(s) associated with each case study so as to increase the exchange of data amongst ice specialists and engineers as well as to improve present knowledge on dealing with ice jams.

By 1985, these tasks were nearly completed with the issue of respective Draft Reports. Copies were sent to interested colleagues for information and comments. The present document is a consolidated issue of all four task reports and incorporates revisions made as a result of comments received.

Since 1985, Working Group members have been preparing a comprehensive Monograph on Ice Jams. This fifth and final task is about to be completed, and publication is expected in the near future.

S. Beltaos
January 1990

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Chapter 1. GUIDELINES FOR RIVER ICE DATA COLLECTION PROGRAMS

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1.1. INTRODUCTION

For a large part of the winter season, ice covers most of Canada's rivers creating numerous and wide-ranging hydrotechnical problems. Detrimental effects caused by the formation, growth and break-up of river ice can be extremely diverse, including for example the forced shut-down of power plants due to frazil accumulation, damage to engineering structures from large ice runs, disruption of normal open water and surface ice transportation, and the flooding of communities by ice jam-induced backwater. Gerard (1979, 1984) and Acres Consultants Ltd. (1971) provide reviews of the myriad problems and the present research associated with river ice.

In purely economic terms, the annual Canadian cost due to ice jams alone has been estimated by Atkinson (1973) to be approximately thirty-seven million dollars*. More specifically, Atkinson (1973) calculated that almost four million dollars* is spent annually on just the repair and maintenance of bridges damaged by ice, and that an even greater damage total of over six million dollars* per year is attributable to flooding caused by river ice jams. While these figures do demonstrate some of the high damage costs associated with river ice, it should be remembered that they are only annual averages derived from a seventy year record. Equally high costs can accrue from a single event. For example, Atkinson (1973) cites a major ice jam on the St. John River in 1936 which resulted in damages of approximately thirty-six million dollars* and, more recently, the total damage which would accrue from a 1:100 year ice jam flood at Fort McMurray, Alberta has been calculated to be over half a billion dollars (Alberta Environment, 1982). In addition to the direct costs

* Atkinson (1973) calculated damages in 1968 dollars. For comparative purposes, they have been converted in this report to 1988 dollars according to the Statistics Canada, Consumer Price Index.

associated with flood damages, river ice problems can produce more indirect costs to the economy such as through the hindrance posed to navigation. In 1984, for example, a financial loss to the shipping industry of over 1.5 million dollars per day was attributed to an ice jam on the St. Clair River by Nekvasil (Globe and Mail, 1984). Although the above-mentioned financial costs associated with river ice problems are exceptionally high, it should be noted that they ignore the less tangible, but no less common, damages such as inconvenience, distress, and even loss of life.

Serious and costly ice problems have occurred on most Canadian rivers where an ice cover develops. The broad national scope of the problem is apparent in a compilation of case studies produced by Petryk (1984, 1990) for the National Research Council of Canada (NRCC), Working Group on River Ice Jams. Evidence from an up-dated review of ice jam related damages in Canada, also being prepared for the NRCC Working Group on River Ice Jams, suggests that the incidence of problems and adverse economic effects associated with river ice will increase as development continues to encroach on southern rivers and extends further into the north.

Despite the economic importance of river ice, research activity has been limited, especially in comparison to the extensive work conducted on open channel flow. In fact, for some hydrological concerns, it would seem more appropriate to focus both data collection and research activities on the period affected by river ice. In the case of high stage events, for example, historical analyses, such as that conducted by Gerard and Karpuk (1979), indicate that maximum annual stages on many northern rivers result not from high flows during the open water season, as is sometimes assumed, but from high stages produced by river ice jams. Effective flood prediction and damage reduction on such rivers can only be achieved by first obtaining the relevant data about the ice conditions period.

Over the last two decades, significant advances have been made in river ice research, particularly with the development of theoretical models of ice jams (Pariset et al., 1966; Michel, 1971; Uzuner and Kennedy, 1976; Beltaos, 1983). Unfortunately, further advances and

even the testing and calibration of existing models have been thwarted by the dearth of quantitative field information.

Good field data are fundamental to this type of research and a comprehensive, detailed data base is needed if significant new advances are to be made in the understanding of river ice processes.

Because of the relative infancy of river ice research, there exists a host of unsolved problems, each of which requires specific types of field data. In most cases, however, there is a 'bottom line' of fundamental field data which has maximum utility in terms of cost-benefit comparisons. The major objective of this report is to present a set of observational guidelines which have been designed around this 'bottom line' and in consideration of the practicalities and logistical difficulties involved in field data collection programs.

In order that the guidelines be usable by as many groups as possible, the observations have been designed for a user who has limited access to a river and who must perform all monitoring from a single bank location. These design criteria ensure that the guidelines can be used equally well in all parts of Canada, including remote areas where access by road and bridge crossings is rarely found. Such physical limitations frequently apply to local observers who conduct auxiliary observations at hydrometric stations. Observational programs of this type should be relatively easy to expand so as to provide for the collection of river ice data.

It should be stressed that this report is directed towards 'site specific' observations whereby the ice observations and data will be used by future researchers and practitioners to study ice conditions at a given site. These types of observations are simpler than and quite different from 'reconnaissance level' observations where sufficient observations are made along the river to understand the ice regime in a given reach. In the detailed study of ice jams, for example, it is 'reconnaissance level' observations which are usually required. A future objective would be to formulate a second set of guidelines for situations in which monitoring of an entire river reach is possible, preferably by aerial reconnaissance, and where additional personnel could be made available during periods of high

activity such as during the formation and release of ice jams. These 'reconnaissance level' guidelines will be designed to supplement the routine or 'site specific' guidelines outlined in this report.

Although the site specific data are not as detailed as the reconnaissance level information, they are still extremely valuable to the solution of a number of research and operational problems. Some of their more immediate utility pertains to the short- and long-term forecasting of the initiation of freeze-up and break-up, and the maximum water levels associated with these events. For example, Beltaos (1990) has had success in developing site-specific forecasting methods, based on a number of years of data of the type described in this report. If similar data is collected from a number of sites, comparative analyses of the site-specific results would most likely lead to techniques for generalization and extrapolation to sites without such historical data. A comparative analysis on a national basis would likely require data from a minimum of 30 sites selected from across the country. The data should be reviewed and appraised at intervals in the order of 5 years.

1.2. DATA COLLECTION PROGRAMS

1.2.1. Other Programs

Recognition of the importance of establishing a comprehensive data base for river ice research is not unique to Canada. Other countries and international agencies have identified the same need and, to varying degrees, have attempted to remedy the situation. For example, the World Meteorological Organization (1981, 1983) provides instructions for the study of river ice as an integral part of its overall guidelines for hydrological programs, including in particular: (a) a suggested network design, instruments and methods of observation; and (b) methods of forecasting, both theoretical and empirical. Unfortunately, the types of ice observations suggested by the WMO are rather elementary and fall short of current requirements. One of the major problems in establishing a comprehensive data collection program in some regions or countries is simply the vastness of the area to be monitored. Strong regional variations in ice conditions and physical environments necessitate the study of

representative river sites from each different region in order to obtain a truly comprehensive data base. Within the U.S.S.R. attempts have been made to regionally classify river ice break-up processes and patterns based on data from a permanent network of monitoring stations. This work appears to be hampered by two factors. Firstly, although there is a large accumulation of material which describes the cause and condition of the formation of spring ice jams, it is primarily limited to qualitative studies of the phenomenon (Deev and Popov, 1981). In recent years, more quantitative analysis has been undertaken in conjunction with attempts to improve the quality and frequency of ice observations at gauging stations (Sofer, 1970). Unfortunately, the number of permanent stations observing ice conditions within the U.S.S.R. is still considered insufficient. Survey by aerial reconnaissance has been suggested as the only current operational facility for obtaining data on river ice regimes over such vast territory (Antonov et al., 1973). One of the most elaborate and extensive field data collection programs focusing on river ice problems is conducted in Hungary (Hungarian Water Conservation Bureau, 1980, 1981). As part of the national water monitoring program, detailed ice observations are regularly conducted by gauge observers at a number of selected river sites. In addition, specially trained ice observation patrols operate along specific river reaches where ice problems are particularly acute. The frequency of patrol observation fluctuates with the seasonal ice cycle and the degree of process activity. Observations are normally conducted on a daily basis during freeze-up, temporarily suspended during mid-winter, and then re-introduced on a continuous basis during spring break-up and periods of ice jamming. The entire monitoring program is supplemented by photogrammetric stations located at selected gauge sites, specially trained observers stationed on ice breakers, and a system for processing, classifying, and storing the observational data.

1.2.2. Canadian Situation

Within Canada there are a number of private and public agencies involved with the collection of river ice field data. On a national

scale, two agencies of Environment Canada, the Water Survey of Canada and the Atmospheric Environment Service, collect ice data from numerous stations across the country. Canada has geographical problems, in terms of scale and regional differences in river ice conditions, which are similar to those encountered in the U.S.S.R. Moreover, much of the data which have been collected by the national agencies suffer from the same shortcomings. Elementary information, such as ice thickness and dates of freeze-up and break-up, is systematically collected but has only limited utility for river ice studies. More detailed quantitative field data have been collected by private consulting firms, hydro-electric companies and other government agencies, such as the National Hydrology Research Institute, the National Water Research Institute, the Alberta Research Council, and provincial conservation authorities. In many cases, however, these agencies have conducted site specific studies focused on a single research interest.

As a result, disparate data are often collected which are difficult to compare and sometimes to access. In response to this problem, Petryk (1984, 1990) has compiled a casebook on ice jams which should improve the accessibility to at least this type of river ice information.

Despite all the data collected in the various case studies and by the national agencies, there still remains a definite scarcity of river ice information about many Canadian rivers and about some important river ice processes. Since it is unlikely in the immediate future that a single agency will be given the mandate to collect the necessary data, the next best step for improving the current data base is to define a set of guidelines for data collection which: (a) can be readily used by any individual or agency interested in river ice processes; and (b) most effectively addresses the needs of current river ice research.

1.3. GUIDELINE DESIGN

1.3.1. General

The set of river ice observations suggested in this report (Section 1.4) are ordered in a typical chronology over the winter months,

although it should be recognized that a river ice regime is a function of climatic and hydro-geomorphological conditions. For example, the process of ice jamming is not exclusively limited to spring break-up, but may also occur during freeze-up and the main winter period, particularly in the warmer, more temperate regions of the country. Frequently, mid-winter melt events can induce break-up and ice jamming which is soon followed by a return to colder winter temperatures and a resumption of the freeze-up processes. For such irregular conditions, use of the guidelines should be adjusted accordingly.

Each temporal phase of the guidelines is introduced by a brief description of the objectives in collecting the data and some indication of their ultimate utility. Figures 1.1 to 1.4 illustrate the types of observations to be conducted at each phase. Uses of these data are quite wide-ranging, and a complete description of their potential benefits is beyond the intended scope of this report. An overall appreciation of their utility can be obtained, however, in the previously mentioned reviews of research priorities. To obtain an introduction to the broad range of river ice literature, readers are referred to Ashton (1980, 1986), U.S. Army (1982) and Michel (1971).

1.3.2. Supplementary Observations

Although the guidelines have been principally designed for use by individual observers who are restricted to making visual observations from a single shore location, it was also recognized that some observers may have access to additional equipment or personnel which would permit the recording of other site-specific information. In particular, two types of supplementary observations -- ice thickness and river discharge -- would be extremely valuable to the understanding of the river ice regime. In the case of ice thickness and stratigraphy, holes would have to be drilled in the ice sheet to permit the measurement of individual snow and ice strata. For most regions, this additional observation could be carried out by a single observer with relatively simple drilling equipment. In contrast, discharge is a much more complicated measurement and requires additional personnel

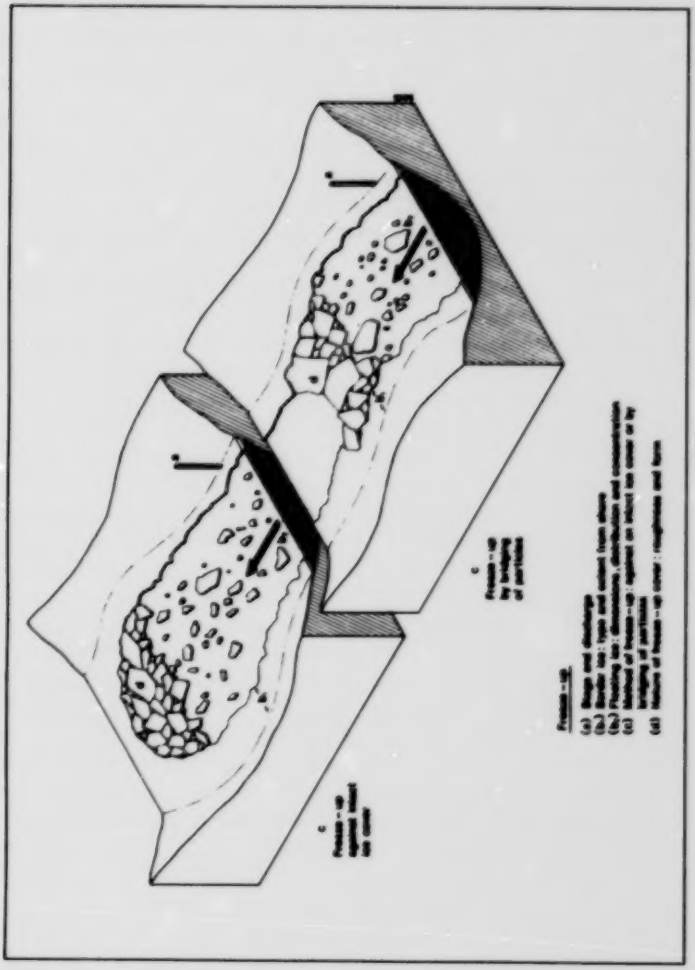


Figure 1.1. Freeze-up observations

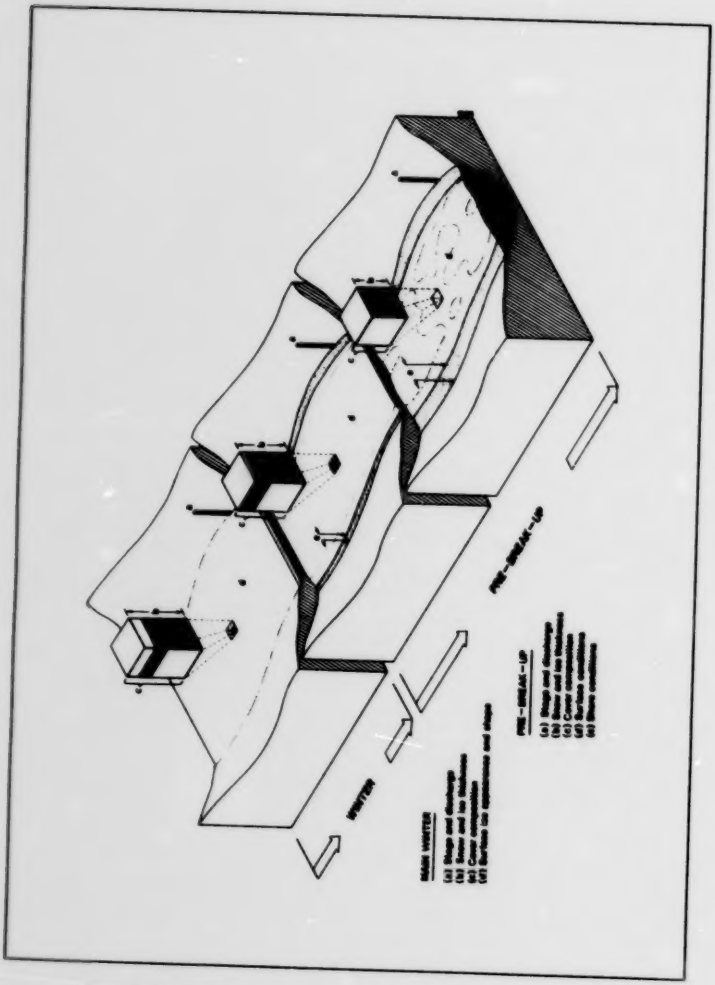


Figure 1.2. Main winter and pre-break-up observations

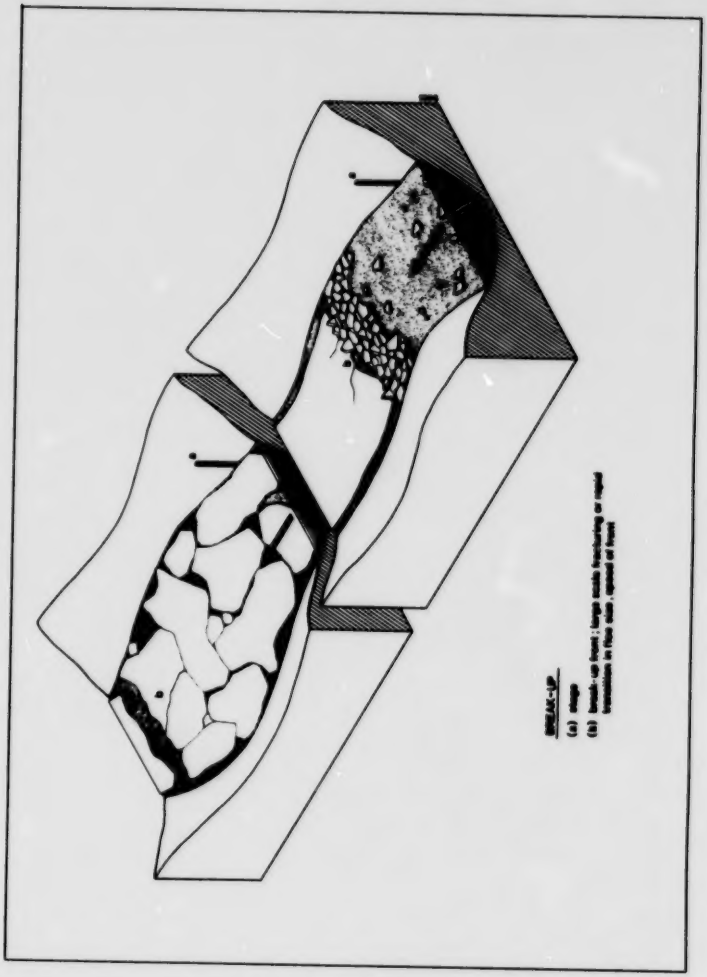


Figure 1.3. Break-up observations

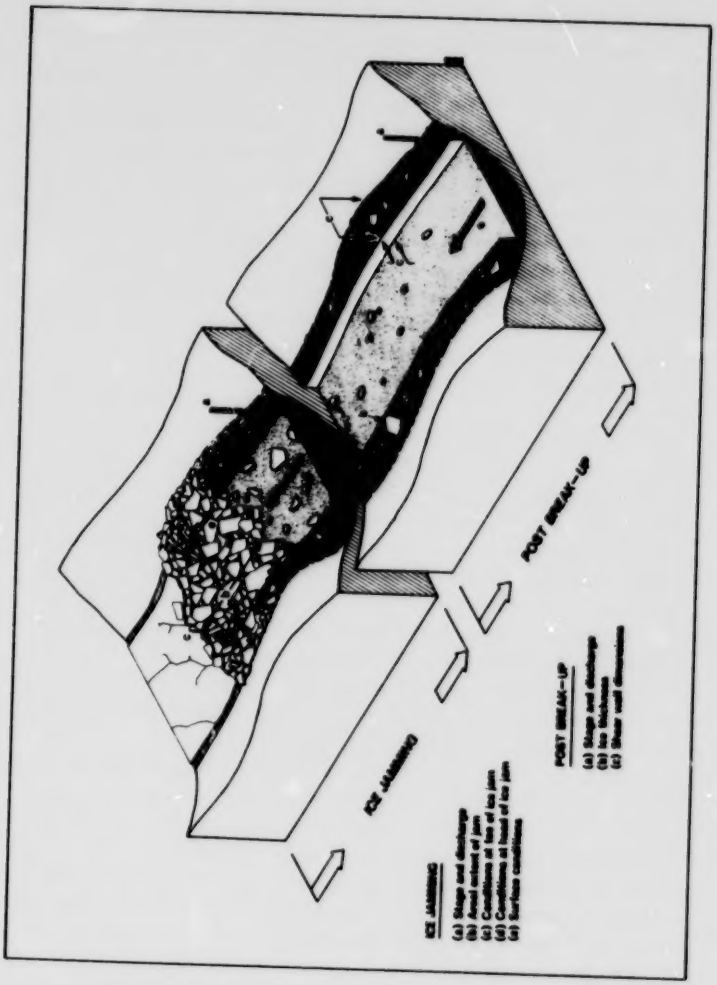


Figure 1.4. Ice jam and post break-up observations

and specialized equipment. Individual observers would not be capable of undertaking field measurements of discharge. Where the personnel and equipment are available, however, it is strongly recommended that efforts be made to obtain direct measurements of discharge.

In view of the importance of these two types of supplementary observations and the number of existing observational programs which could record this type of information, appropriate data collection guidelines have been included in Section 1.4. For individual observers who lack the necessary additional equipment or personnel, these supplementary observations will have to be forgone and the remainder of the shore-based observations conducted as outlined.

1.3.3. Selection of Study Sites

A high proportion of the users of these guidelines are expected to be agencies or organisations which already operate some form of hydro-data collection program. In such cases, the river ice observations will probably be incorporated as part of an existing data collection program, and the location of observation sites will therefore be pre-determined. Notably, however, the combining of programs may affect the type of ice observation data which are collected. For example, the Water Survey of Canada normally selects straight river sections, devoid of any major obstacles to flow such as islands or shoals, at which to establish gauging sites. The probability of collecting observations of ice jams at such sites may therefore be low. In cases where new study sites are being selected, or existing data collection programs are being expanded, a number of selection criteria should be considered which will assist both in the monitoring of river ice conditions and in future research analyses. Firstly, a river gauging site and meteorological station, both with reliable records, should be in close proximity. Sites with more than one good vantage point from which to conduct upstream and downstream observations are preferred. Access to a bridge is ideal and creates the added opportunity of obtaining discharge measurements immediately following, and possibly during, break-up.

If a number of sites are to be selected and studied by one agency, care should be taken to obtain a varied sample of representa-

tive reaches from the whole study region. In terms of a national program, representativeness should be addressed under such categories as river size, geomorphology and climate.

1.3.4. Frequency of Observations

In situations where ice observations are incorporated as part of an existing data collection program, the timing of observations may be largely controlled by the established frequency of site visitation. It should be remembered, however, that one of the major reasons for the scarcity of good field data from some water data collection programs is the relatively low frequency and untimeliness of site visits in comparison to the degree of river ice activity. Perhaps the scheduling of some existing field programs could be modified to allow for more frequent site visits during the river ice period, particularly during freeze-up and break-up.

If incorporating additional visits and observations within existing programs is not logistically feasible then perhaps additional field personnel primary objective is to conduct observations during the river ice period could be made available.

The frequency of site visits should ideally correspond with the degree of river ice activity. During freeze-up, daily visits should be made. Once an intact ice cover has been established, visits can be reduced to one every two or four weeks, the frequency increasing as the break-up season approaches. After appreciable melt has occurred, observations should again be conducted on a daily basis with as many observations per day as possible during the main break-up period. Further details regarding the frequency of specific observations are included in Section 1.4.

1.3.5. Survey Forms

Appendix 1.A contains two examples of forms which have been developed to assist in the collection of river ice observations. The first form, 'ICE SURVEY NOTES', is a modified version of an earlier form (Anderson and Prowse, 1983; Prowse and Anderson, 1984) which was designed to be compatible with the standard field measurement forms used by the Water Survey of Canada. The rows and columns on p.1

(Appendix 1.A) are for entering thickness data from a cross-section profile of a stable ice cover. These data can normally be collected when holes are drilled through the ice for the measurement of discharge. As earlier noted, such measurements can only be conducted in cases where the personnel and appropriate equipment are available. The remainder of the form can be completed by an individual making observations from a bank location. Spaces and appropriate headings are included to assist in recording most of the observations outlined in this report. Separate parts of the form are devoted to the recording of freeze-up, break-up, and ice jam observations. The second form (Beltaos, 1984) can also be used by a shore observer and is broken primarily into sections on open water, moving ice and stationary ice.

One important feature of both forms is the inclusion of space for sketches of river ice processes and a note indicating that photographs should be taken whenever possible. Any form of imagery, whether hand-sketches or photographs, is invaluable to the final interpretation and analysis of the data, especially where this work is conducted by someone other than the ice observer.

1.4. GUIDELINES - ICE OBSERVATION PHASES

1.4.1. Freeze-up

During freeze-up, accumulation of ice within a river changes the open water relationship between stage and discharge. The degree of distortion is primarily dependent on the form, thickness and roughness of the accumulating ice cover. Knowledge of the freeze-up processes is critical to the interpretation of stage records, the assessment of discharge, and ultimately to predictive modelling of freeze-up. Freeze-up characteristics have also been shown by Shulyakovskii (1966) and more recently Beltaos (1990) to have important ramifications for break-up. In particular, the stage required to initiate break-up and the maximum stage reached during break-up have been found to be closely linked to the stage at freeze-up. Even the structure of the freeze-up ice cover can be

important to the decay and fracturing of the ice cover at break-up.

The main types of observations to be taken during freeze-up include: stage, discharge, ice types, concentration, method of freeze-up, nature of the ice cover formed, and rate of upstream progression (Figure 1.1).

a) Stage and discharge: Monitor the stage leading to freeze-up, particularly at the time of formation of the first permanent ice cover. Under some conditions, the annual peak stage occurs during freeze-up. Measure or estimate discharge before and after freeze-up.

Photograph 1.1

Growth of border ice along the bank with frazil pans flowing in open channel: North Saskatchewan River (courtesy: D. Andres, Alberta Research Council)

b) Ice types and concentration (Photograph 1.1)

Border ice: Border ice is composed of ice which has gradually grown outwards from the shore or from exposed objects in the channel, and/or from drifting ice (primarily frazil ice) which has accumulated along the ice-water margin. Where border ice is subject to water level fluctuations, repeated flooding and freezing of river water can produce a layering of abnormally thick ice along the banks. Note the type, thickness and lateral extent of border ice.

Floating ice: Estimate the dimensions, distribution, and concentration of frazil (or other) ice passing through the river reach. Where close inspection of the ice can be made, provide a qualitative estimate of ice strength and porosity. In the case of frazil pans, note the thickness of the overall pan and the surface crust.

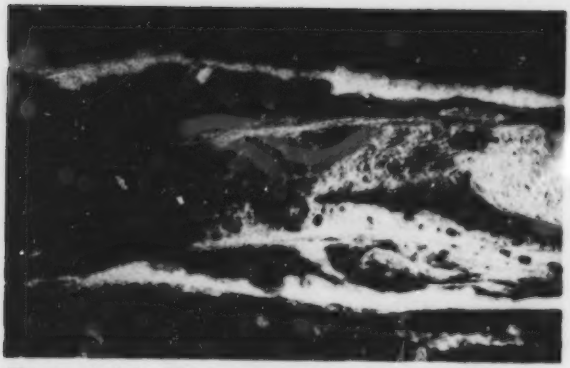
c) Method of freeze-up: Describe whether the formation of the final complete ice cover results from the lodgement or bridging of ice particles across the section or from the accumulation of ice particles against a downstream ice cover (Photographs 1.2, 1.3 and 1.4). Note the rate of upstream progression of the freeze-up front through the observable river reach.

d) Nature of freeze-up ice cover: Describe the surface of the final ice cover with particular reference to surface roughness and ice types. Estimate overall thickness.

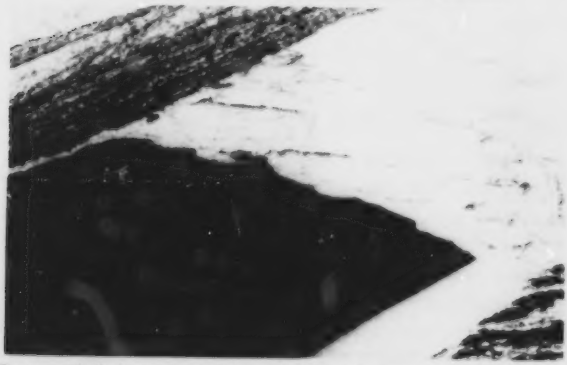
Photograph 1.2 Large ice pans pinching main channel which has heavy discharge of slush: Liard River (courtesy: P. Parkinson, Lasalle Hydraulic Lab. Ltd.)

1.4.2. Main winter period

Ice growth during the winter season determines the quantity and strength of ice which must be removed at break-up. Since break-up does not necessarily occur at the same time each year, and ice thickness may vary depending on the severity of winter conditions, regular monitoring of ice thickness is necessary. Because of spatial variations in ice thickness, a number of measurements taken across the river cross-section is preferred. In cases where such



Photograph 1.3. Floe arrangement in freeze-up ice cover. Note extent of border ice and assortment of floe sizes in accumulation: North Saskatchevan River (courtesy: D. Andres, Alberta Research Council)

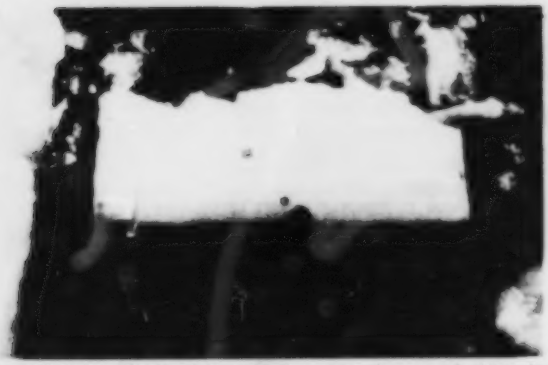


Photograph 1.4 Accumulation of floes in centre of channel. Note successive shear lines in border ice: Liard River (courtesy: P. Parkinson, Lasalle Hydraulic Lab. Ltd.)

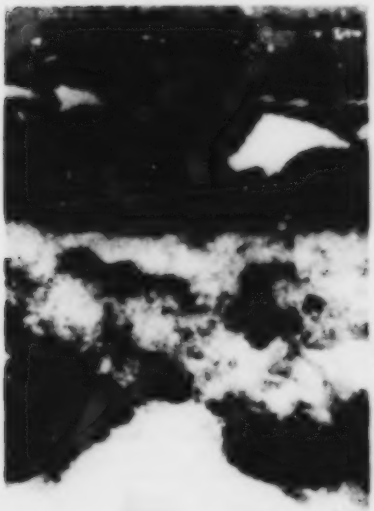
measurements are taken as part of a vinter discharge measurement, the total ice thickness (i.e., top to bottom of ice cover) should be measured rather than the common measurement of the thickness of ice beneath the water surface which is used in deriving the depth of flov beneath an ice cover.

Attempts should also be made to record the general stratigraphic composition of the ice cover when thickness is measured. In the simplest case, (Photograph 1.5) the top of the ice cover will be comprised of an upper strata (often multiple layers) of relatively opaque, white ice formed from frazil accumulations at freeze-up and the slushing and refreezing of surface snow. Beneath this ice will be a more transparent 'blue' or 'black' ice formed by the downward freezing of river water. The interface between these two strata can best be observed by drilling a hole part way into the ice cover, so as not to allow water to fill the hole, and then inspecting the side of the drill hole. In addition to differences in visual appearance, these two layers are distinguishable by differences in texture along the side of the drill hole. The surface layers of white ice will be characterized by a rough granular texture while the underlying layer of black ice will generally be much smoother. Once the location of the interface between these two layers is determined, drilling of the hole can be completed and total ice thickness measured. The presence of frazil ice accumulations beneath the main ice cover should also be noted (Photograph 1.6). The thickness of frazil ice beneath the ice cover can usually only be determined from vertical profiles of water velocity beneath the ice cover.

It should be stressed that the above describes only the simplest case of river ice stratigraphy. The composition of river ice is often so complex that observers will be able only to accurately measure total snow and ice thickness. Where an ice cover has evolved from a complex assortment of freeze-up and growth processes, identification of major strata can only be accomplished by extracting an ice block or ice core, a procedure which requires resources beyond those described for this set of guidelines. Further discussions of river ice types can be found in, for example, Ashton (1979, 1986) and Michel (1971).



Photograph 1.5. Block of ice showing upper layers of white ice overlying transparent black ice. Bottom of white ice can be seen through top layer of black ice (Author)



Photograph 1.6.

Accumulation of frazil deposits beneath main ice cover. Note high bubble content in black ice (centre) in comparison to that in previous photograph (Author)

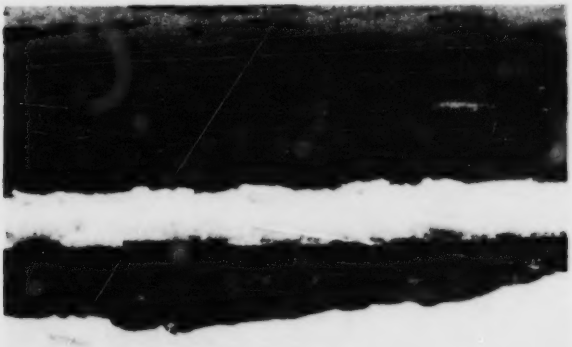
The major types of observation to be taken during the main winter period include: stage, discharge, snow and ice thickness, ice cover composition, and surface ice appearance and shape (Figure 1.2).

a) Stage and discharge: Monitor the stage during the winter period paying particular attention to periods when the ice cover drops, because of recession in flow and erosion of frazil deposits, and forms hinge cracks (Photograph 1.7). Discharge measurements should be made frequently enough to produce a reliable discharge recession curve.

b) Snow and ice thickness: Measure the thickness of the surface snow cover and thickness of the underlying ice cover at a number of points across the river cross-section.

c) Cover composition: When measuring ice thickness, note the thickness of different ice layers and the presence of frazil accumulations beneath the main ice cover.

d) Surface ice appearance: Note the surface roughness of the ice cover, including the location of pressure ridges and other areas where the ice appears to be grounded, and the presence of shear lines along the shore.



Photograph 1.7. Hinge crack formed at freeze-up from a recession in water levels. Hinge cracks may also form after a complete ice cover has developed: Mackenzie River (Author)

1.4.3. Break-up

Systematic documentation of break-up conditions over a number of years will lead to a refinement of existing classifications of break-up processes and to a better understanding of the physical mechanisms which control break-up. One of the more immediate benefits of the data will be the opportunity to develop site-specific forecasting capability of ice conditions. Over the longer term, the probability of specific break-up events will hopefully be linked to measurable morphological and hydrometeorological characteristics which can then be used to extrapolate forecasting capabilities to other areas.

Of all the break-up observations, special efforts should be made to obtain accurate records of maximum stage. For most rivers, break-up is typically the period with the poorest stage record because of the damage to stream-implanted recording devices by moving ice. Manual surveys of stage should be conducted during each visit and notes made of any recent high water marks or strand lines. Where resources permitted, crest-stage gauges and time-lapse cameras have been used in attempts to improve the stage record during break-up.

Because ice jams are responsible for the highest water levels on many rivers, information should be collected regarding their mode of initiation and failure, their effect on stage, and even their size in terms of elementary parameters such as length, depth, and width. This type of information will provide direction to further field, laboratory and theoretical studies.

Because of the complexity of the break-up process, observations have been broken into four periods: pre-break-up, break-up, ice jams and post break-up. The possibility of obtaining many of the listed observations depends on the position of the observer relative to specific break-up forms and processes, particularly ice jamming.

1.4.3.1. Pre-break-up (Figure 1.2.)

a) Stage and discharge: Stage should be measured daily until the water level approaches the freeze-up level. The frequency should then be increased (every eight to twelve hours) especially if mild weather has set in and significant attendant runoff is anticipated. Special efforts should be made to obtain a flow measurement as close to the time of break-up as possible.

b) Snow and ice thickness: Once the main snowmelt period has begun, a final survey of snow and ice thickness across the reach should be made before the surface becomes unsafe for travel.

c) Cover composition: In conjunction with the final thickness survey, note the thickness of the different ice layers including surficial ice forms and frazil accumulations beneath the main ice cover. As water begins to saturate the snow and ice, individual strata will become increasingly difficult to distinguish.

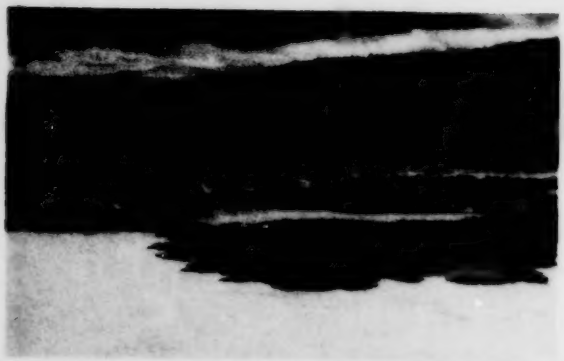
d) Surface conditions: Once surface travel is unsafe, note the percentage cover of snow and exposed ice, the presence of ponded meltwater, and when the water drains from the surface. The ice surface often has a dark appearance when covered with meltwater but quickly brightens after draining.

e) Shore conditions: Note the depth and width of any water accumulating near the shore and if any flow is apparent. Also describe the formation, size and position of any major cracks, and note when the main ice cover 'lifts' and detaches from the shore. Lifting of the ice sheet is usually concomitant with the draining of surface meltwater. Note whether bottom fast ice is present beneath the shore lead.

1.4.3.2. Break-up (Figure 1.3)

a) Stage: Water levels should be monitored as frequently as possible. Points of specific interest include: the rate of rise in water level immediately prior to the initial fracturing and movement of the ice sheet, water levels at the time of first ice movement, the maximum break-up water level, and changes in water level as fractured ice clears the study reach.

b) Break-up front: The character of a break-up front can vary considerably but there are usually two distinct styles. The first involves a rapid transition from intact ice cover to highly fractured ice (Photograph 1.8). In such cases estimate the rate at which this fractured break-up front moves downstream. The second style is characterized by a large scale fracturing of the ice sheet followed by a downstream movement of large pans which often rotate and fracture within the flow (Photograph 1.9). In this second case, estimate the speed at which the initial pans move downstream. In extreme cases (thermal break-ups) the ice cover will almost melt *in situ* (Photograph 1.10).



Photograph 1.8. Break-up front showing a rapid transition from intact ice to heavily fractured ice. Front was advancing in excess of 5 $m \cdot s^{-1}$: Liard River (Author)

Photograph 1.9. Break-up front characterized by large-scale fracturing of the intact ice sheet and downstream movement of large ice floes: Liard River (Author)

1.4.3.3. Ice jams (Figures 1.4 and 1.5)

In cases where the clearance of fractured ice from the study reach suddenly stops, formation of a jam downstream can be assumed. The type of observations to be taken then depend on the position of the observer relative to the various parts of the jam. If the observer

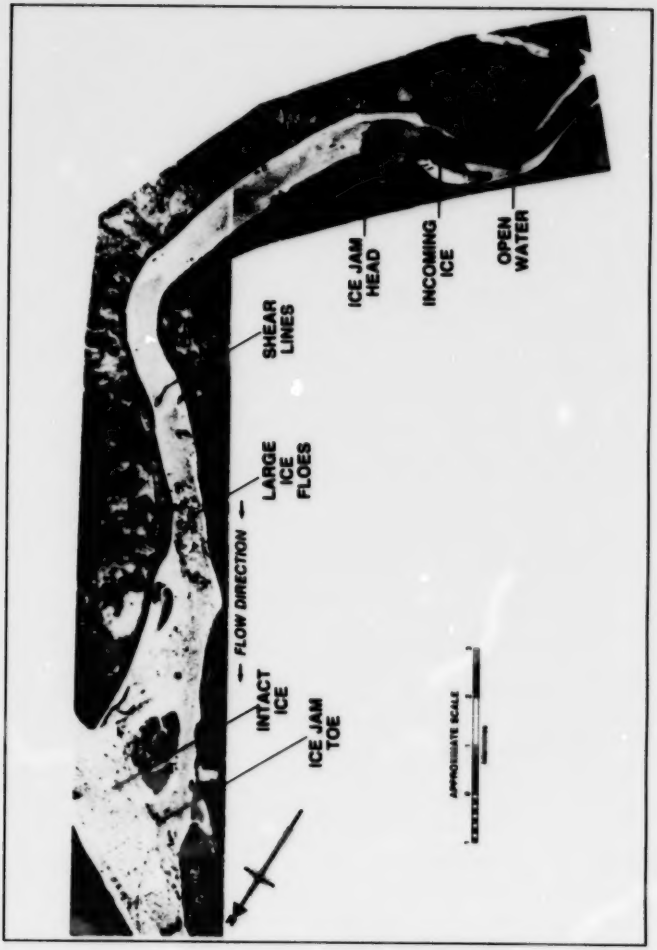


Figure 1.5. Component of an ice jam (confluence of Liard and Mackenzie Rivers)

Photograph 1.10. Break-up occurring from *in situ* thermal decay of the ice cover. A situation similar to that which occurs on lakes: Liard River (Author)

has good vantage of other parts of the river, or access to other sites, every effort should be made to observe as much of the ice jam as possible. Even where observations are limited to one site, if final clearance of the jam can be monitored, the observer may be able to estimate what the other characteristics of the jam may have been, such as location of the head (upstream end of ice jam, see Figure 1.5) and jam length.

a) Stage and discharge: Water levels should be monitored as frequently as possible. Points of specific interest include: the rise in water level when the moving ice stops, the maximum water level while the jam is in place, and the water level when the jam breaks and ice again begins to clear from the reach.
   If other points are accessible along the ice jam, make notes of the water level at each site relative to local objects which can be surveyed later to obtain real elevations.
   Estimate the velocity of the break-up front which led to the formation of the ice jam and the velocity of surface ice when the ice jam releases.

b) Areal extent of ice jam: Note whether the ice completely or only partially blocks the river cross-section. If visible, also record the location of the downstream (toe) and upstream (head) portions of the jam (Figures 1.4 and 1.5)

c) Conditions at toe of ice jam: If the ice jam toe is visible, describe whether the jam has been either: (i) forcibly halted by some downstream obstruction, such as an intact ice cover (see Figure 1.5), man-made structure, geomorphological feature (shoal, sharp bend), etc.; or (ii) stopped by the lodging or bridging of ice floes across the river channel (similar to freeze-up situation in Photograph 1.2). If possible make a discharge measurement downstream of the toe where no backwater effects are apparent.

d) Conditions at head of ice jam: If the head of the ice jam is visible, estimate the size (dimensions of floes) and concentration (percentage of river surface covered) of incoming ice. Also note whether the ice is adding to an upstream extension of the jam or is being entrained underneath the jam. If possible make a discharge measurement upstream of the ice jam (see notes under post break-up).

e) Surface conditions: Note the roughness and texture of the ice jam surface. Estimate the distance from shore of any shear lines which have formed from differential movement within the ice jam. Attempt to identify whether the jam is comprised of a single layer of floes or if there has been noticeable compaction and thickening of the jam. Note also if the surface is 'buckled' or has localized ice mounds. This may indicate that ice is grounded on the river bed. Record the presence of any major ice shoves (Photograph 1.11).

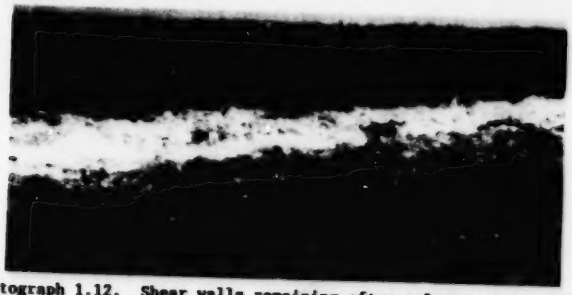
Photograph 1.11. Ice shove into trees along river banks at break-up. Upper point of ice is 10 m above the main break-up level: Mackenzie River (Author)

1.4.3.4. Post break-up (Figure 1.4)

a) Stage and discharge: Continue regular monitoring of water levels until the majority of floating ice has completely cleared from the study reach. Discharge measurements during the active break-up period are normally not available for hydrometric sites in Canada, largely because of the lack of safe access and the relatively short duration of the break-up period. Where access is available, such as from a bridge spanning the river reach, discharge should be measured as soon as the river becomes sufficiently clear of floating ice to allow the lowering of current meters. Details should be provided regarding the stability of the flow at the time of the measurement and the relative location of any ice accumulations in the river both upstream and downstream of the measurement site. Observations of stage and discharge should continue until backwater effects due to ice disappear.

b) Ice thickness: Measure the thickness of ice floes which have been stranded along the shore. Where possible use ice floes which show a complete stratigraphy and disregard those which have been sheared in cross-section or badly deformed by ice jam forces. Provide a brief description of the quality or structural integrity of the ice floes, such as whether the ice is heavily candled or remains relatively competent.

c) Shear wall dimensions: Following the clearance of an ice jam, there often remain large masses of strongly deformed ice which have been 'plastered' along the shore. The outer edge of these masses is normally marked by a very precipitous edge termed the shear wall (Photograph 1.12). Once the water level has receded, to the point where the base of the shear walls becomes exposed, measure or estimate the overall height of the wall and its distance from the channel bank. This gives a good indication of ice jam thickness, a parameter of crucial importance in ice jam research.



Photograph 1.12. Shear walls remaining after release of ice jam. Walls are approximately 8 m high and give good indication of ice jam thickness: Liard River (Author)

1.5. SUMMARY

This set of data collection guidelines was developed in response to an expressed need for a coherent and extensive data base concerning river ice processes. The existing data base is unsatisfactory because of the brevity of most site records, the lack of uniformity in the types of collected data, and the scarcity of detailed information for many parts of the country. The structured format of these data collection guidelines will hopefully lead to the assembly of a uniform data base beneficial for operational as well as research purposes.

The observations have been selected based on the needs of current and future river ice research, while also considering the difficulties and practicalities of field monitoring programmes. In general, the observations can be made by a single individual who has only limited access to a river. This criterion ensures wide-spread usability of the guidelines.

The next step in developing a comprehensive data base will be the design of a further set of 'reconnaissance level' guidelines which can be used by agencies and researchers for more intensive studies of a smaller number of sites. At this level, entire river reaches will be monitored and much more elaborate observations will be possible with additional personnel and equipment. The more sophisticated set of observations will serve to augment, rather than replace, those outlined in this report.

1.6. ACKNOWLEDGEMENTS

Contributions and reviews by members of the NRCC Working Group on River Ice Jams (Foreword), M. Alford and L. Kamp of the Water Resources Branch, J.C. Anderson, D.K. MacKay and C.R. Onclin of the National Hydrology Research Institute, and Dr. W.P. Adams of Trent University are gratefully acknowledged. Special thanks to S.C. Gardiner of Trent University for the illustrations.

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APPENDIX 1.A

ICE SURVEY NOTES

p. 1

ICE SURVEY NOTES

Station..... Sta. No. .....

Date:.../.../... Time.....(....)
Yr Mo Dy Zone

Party..... Agency.....

Air temperature.....°C Water temperature .....°C

Water stage.....Datum.....m Discharge.....m^3/s
or
Velocity estimate.....m/s

ICE QUANTITY

Initial Reference Point: .....

Hole No.	Distance from Ref. Pt. (m)	Snow Depth (m)	Solid Ice Thickness			Frazil or Slush Ice (m)	Water	
			White Ice (m)	Black Ice (m)	Total Ice (m)		Surface to top of ice (m)*	Total Depth (m)
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
Mean								

Final Reference Point:.....
Channel Width:.....m

* positive if water above ice surface; negative otherwise

FREEZE-UP

Event	Timing of Event ☐ observed ☐ estimated				Water Stage (m)
	Yr	Mo	Dy	Time	
Initial ice formation					
Complete freeze-over					
Peak Stage					

Presence of: ☐ Border ice: growth from shore .....m

☐ Shear lines in ice cover: distance from shore .....m

☐ Moving ice: Types ☐ slush ☐ pancakes ☐ floes ☐ large sheets ☐ other.....

Concentration of moving ice .....% of open channel width

CHARACTER OF INTACT ICE COVER

Surface Roughness: (circle one)

Relief				
smooth	<0.2m	<0.5m	<1.0m	>1.0m
1	2	3	4	5

Decay (circle one)

Degree of Decay			
snow covered	melting snow	melting ice	candled ice
1	2	3	4

Evidence of Fracturing along Bank: ☐ No ☐ Yes:

a - ice thickness when fracture occurred: .....m

b - displacement:....m

c - distance from shore: .....m

BREAK-UP

Event	Timing of Event				Water Stage (m)
	□observed □estimated				
	Yr	Mo	Dy	Time	
Shore lead formation					
Transverse cracks or leads					
Peak stage					
Main ice cover first moves					
Water clear of ice					

ICE JAMS

Event	Timing of Event				Water Stage (m)
	□observed □estimated				
	Yr	Mo	Dy	Time	
Jam initiated					
Jam present					
Peak stage					
Jam releases					

Jam Obstruction: □solid ice sheet □island
□bend □other.....

Shear Lines: distance from shore .....m

Jam Length .....km Note position of ice jam toe (downstream end) and head (upstream end) on sketches, if possible.

Post Jam: Height of shear walls along bank .....m

SKETCHES: Include approximate scale.
Illustrate eg. character of ice cover, ice coverage, water level, etc.

1. River Cross Section

downstream view

2. River Reach (Use copy of map if available; show flow direction)

COMMENTS on any aspect of ice quantity, quality, freeze-up, break-up, jamming, weather, etc.:

.....

.....

.....

.....

PHOTOGRAPHS: ☐ No ☐ Yes: (available from).....

Subject(s):.....

RIVER ICE MONITORING FORM

Site _____ Observer _____ Date _____ Time _____

Staff Gauge (if applicable) _____ m at _____ h

ICE CONDITIONS

Open Water: Yes/No. Where _____

Moving Ice: Yes/No. Where _____

What Kind:[1] Slush/Pancakes/Large Sheets/Floes/Small Blocks/Other _____

Stationary Ice: Yes/No. Where _____

What Kind: Pancake Ice/Sheet Ice/Blocks (Jam)/Other _____

Ice Thickness:[2] _____cm Ice Quality:[3] _____

Snow Cover: Yes/No. Approximate Depth _____ cm

Photo (Looking Upstream/Downstream/Left Bank/ Right Bank) or Sketch. Time _____h

Other Notes:[4]

(1) Underline one or more items.
(2) Give values as measured across the channel, if applicable.
(3) Use such words as competent, deteriorated, candled.
(4) Record such additional information as water on top of ice; unusually fast or slow current; presence of ice jam and locations of upstream and downstream ends if visible; overbank flow; presence and configuration of shear walls; etc.

Chapter 2. GUIDELINES FOR EXTRACTION OF ICE-BREAK-UP DATA FROM HYDROMETRIC STATION RECORDS

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2.1. INTRODUCTION

A major consequence of ice cover formation in rivers is the jamming that occurs during spring break-up of the ice cover. Because of their large aggregate thickness and hydraulic resistance relative to those of sheet ice, jams can cause very high water stages. This has repercussions in many operational and design problems such as flooding and associated flood risk assessments; overturning moment applied to river structures by moving ice floes; bed scour due to surges from ice jam releases; and many others.

The available technology to deal with problems related to ice jams is very limited. This reflects the great complexity of ice jamming processes and Kennedy's (1975) observation that "...an ice-jammed river is among the most deranged of hydraulic phenomena" is still valid today. This complexity of ice jamming phenomena imposes a serious limitation on the type of pertinent research that can be performed, that is, it renders reproduction of all, or even most, of the pertinent factors in the laboratory very difficult. As a result, laboratory experimentation on ice jams must be limited to the study of specific, isolated aspects in cases where field observation has helped identify the basic processes involved. As an example, one could cite the case of ice jams formed entirely by submergence of ice blocks. In this instance, laboratory tests can furnish useful data on the thickness and thence the water stage of such jams. However, this knowledge only addresses a very small part of the entire problem which can be stated briefly as follows:

> "In a given ice covered reach, increased runoff and mild weather are anticipated in the next few days. Forecast whether and when ice break-up will be initiated; forecast locations, durations and peak stages of any ice jams that might occur; forecast when the break-up will be completed."

Clearly, the study of river ice jams must be based, to a large degree, on field observation and data. This perception has recently become a general one among hydraulic engineers so there is good reason to expect increased monitoring activities in the future. However, development of an adequate base of field case studies will require many years after a national-scale observation program has been initiated.

In the meantime, it would be desirable to consider other sources of field data that might already by available. One such source is the hydrometric gauge data obtained routinely by the Water Survey of Canada (WSC) and by other agencies throughout a national gauge network. This source is imperfect (ice effects are only documented to improve discharge estimates) but has two attractive features: it is available readily at little cost; and it adequately covers the Canadian ranges of stream and weather types.

Earlier work (Shulyakovskii, 1966; Beltaos, 1981, 1982; and Beltaos and Lane, 1982) has shown that this approach has good potential for development of needed forecasting methods. Achievement of this potential, however, requires analysis, interpretation and comparison of data from many gauge sites. This report provides guidelines for extracting ice-related information from the hydrometric records in the hope that others may be encouraged to carry out such studies so as to accelerate the formation of an adequate data base. Examples of utilising the results of the analysis are included for illustration purposes. As a by-product, instances are identified where minor additions to gauge operation procedures would substantially improve the utility of the records.

2.2. RIVER ICE BREAK-UP

When an ice-covered river basin is subjected to mild weather, two major processes generally begin:

i) Increased runoff by either snowmelt or rainfall, or both.

ii) Increased heat input to the ice cover.

The former process results in increased uplift and frictional forces applied to the ice cover and in increased water stage which, in turn, reduces contact between the ice cover and the channel banks and provides increased channel width for movement of the ice cover. Net heat input to the ice cover results in reduced dimensions and strength. It follows that during the mild weather spell, the forces applied on the ice cover increase while the cover's ability to resist these forces decreases. If the mild weather lasts for a sufficient time, the ice cover begins to break up which is often followed by formation of large ice jams, major ice runs and eventual clearance of the ice from the reach of interest. This general description of the break-up process includes two extreme cases, i.e., the "premature" and "overmature" break-up (Deslauriers, 1968). Premature break-up occurs under conditions of intense runoff with little, if any, prior deterioration of the ice cover. Clearly, this type of event has the greatest damage potential, other things being equal. On the other hand, conditions of slow or no runoff with intense ice deterioration lead to overmature break-up. This event is characterized by gradual ice disintegration and has minimal potential for damage.

The first question a forecaster might ask would be how to predict whether and when break-up will be initiated and, once initiated, how severe it is likely to be in terms of magnitude and duration of ice jam stages at various locations.

Concerning break-up initiation, pertinent literature often advocates use of the corresponding water stage, H_s (= height above an arbitrary datum, e.g., gauge height) as a convenient and meaningful index (Shulyakovskii, 1966; Gerard, 1979; Beltaos, 1981, 1982). From our earlier discussion, it would appear that H_s is indeed a desirable parameter because it reflects the ice driving forces as well as the water surface width available for ice movement. Moreover, the above noted literature suggests that, in a given reach, H_s depends on: the thickness of the ice just prior to break-up, h_i; the degree of ice strength reduction caused by thermal effects; and the stage during freeze-up when a stable ice cover forms, H_f. The latter is a measure of the width of the ice cover and, excepting mature break-up events, has to be exceeded before contact of the ice with channel boundaries

is eliminated. As will be discussed later, approximate values of these parameters can be extracted from gauge records. As for ice strength, there is no direct information. The best that can be done at present is to use a meteorological index intended to reflect the effects of thermal deterioration.

With regard to the severity of break-up, one would ideally wish to predict the complete stage hydrograph during the break-up period, at any given location. This appears to be too ambitious a task at present; it is thought more practical to limit the goal of the study to forecasts of the maximum stage during break-up, H_m. This stage can easily be identified on gauge recorder charts and is usually caused by a nearby ice jam. Theoretical considerations and field data (Pariset et al., 1966; Beltaos, 1983a) have shown that the maximum stage that can be caused by an ice jam occurs when the jam has attained a condition of equilibrium and fully affects the site of interest. This equilibrium stage depends mainly on discharge as well as channel slope and width. During any one break-up period, H_m may or may not reach the equilibrium jam stage owing to one or more of the following reasons:

i) Ice jam is located far downstream of the gauge site. Even if this jam attains equilibrium, the gauge site will experience a fraction of the jam's effect on stage.

ii) Ice jam is located far upstream of the gauge site. The gauge site will again experience a fraction of the jam's effect on stage owing to attenuation effects during the jam's release.

iii) A jam that releases prior to attaining equilibrium.

iv) Overbank flooding. Water and ice spread out onto the flood plain so that the jam's potential is dissipated.

Considering that a major factor contributing to ice jam formation and persistence is the presence of intact sections of sheet ice cover, it is reasonable to expect that not only discharge but also the competence of the sheet ice cover may influence the value of H_m (see also later discussion).

The preceding discussion has identified several parameters that can be determined from existing data and that can be expected to be related to important ice jam features.

2.3. DESCRIPTION OF EXISTING DATA

The following data are routinely obtained throughout the year at any one gauge site.

2.3.1. Stage Record

At automatic recording gauge sites, a continuous stage versus time chart is available. Our main interest is in the ice cover period which occasionally may contain intervals of missing records owing to malfunctions caused by the ice. This limitation may be too severe at some gauge sites to enable data analysis but there are many other sites where such malfunctions are minimal.

2.3.2. Local Observers' Reports

At many gauge sites, local observers are temporarily employed by the operating agency to provide brief descriptions of ice conditions at a specified frequency. This information is extremely useful, especially in cases where interpretation of the stage record is difficult.

2.3.3. Discharge Measurement Notes and Ice Thickness

During the ice cover period, discharge measurements are made periodically to enable calculation of daily values. Since open-water stage-discharge relations do not apply during this time, a number of interpolative techniques are used to calculate the daily discharges. Additional information, such as flows at adjacent sites, precipitation, and temperature, is also used in the calculation.

These calculations may be in considerable error during periods of intermittent ice cover or periods of highly unsteady flow such as during the break-up period. Examination of the timing of discharge measurements with respect to the calculated discharge hydrograph during the ice cover and break-up periods, and examination of the measurement notes themselves, help to assess the reliability of the calculated daily discharges.

In addition, the discharge measurement notes can be a useful source of ice thickness data because the distance from the water surface to the bottom of the ice cover is recorded at each measurement hole. Under free-flotation conditions, this quantity represents

about 95% of the total ice thickness. In reality, this relationship may not be valid owing to one or more of the following possibilities:

i) Significant bank support of the ice cover.

ii) Snow Cover.

iii) Slush deposit under the solid ice layer. The notes would only show the distance from the water surface to the bottom of the slush layer.

iv) Unreported instances where "water surface" has been used nominally, i.e., substituted by a more convenient datum such as the top of a deep snow layer.

It is very difficult to select an accurate value for the submerged to total thickness ratio of a solid ice sheet, without knowledge of local conditions. Often, the water surface rises to the top of a hole cut in an ice sheet and, sometimes, even above it. (This can be caused by a deep snow layer, for example.) Perhaps the best approach would be to agree on a value of the desired ratio and use it as a matter of convention. For example, a value of 0.96 or 0.97 would seem a fair compromise since it could not be in error by more than a few percent.

Clearly, future measurements of the distance from the water level to the top of the ice cover and the solid versus slush ice fractions would provide more reliable thickness values.

2.3.4. Meteorological Records

In addition to hydrometric records, meteorological information is needed from a nearby weather station to define an index for ice strength. Meteorological data may be found in the publication "Monthly Records" that is issued by the Atmospheric Environment Service of Environment Canada.

2.4. EXTRACTION OF INFORMATION RELATED TO BREAK-UP

After the necessary raw data have been gathered, a number of pertinent parameters can be extracted, as outlined next.

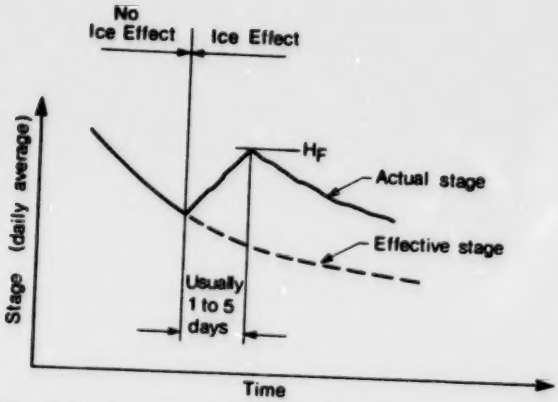

Figure 2.1. Schematic illustration of daily stage variation with time during beginning of freeze-up

2.4.1. Stable Freeze-Up Stage (H_F)

A typical but not universal configuration of the daily average stage hydrograph near the start of the ice season is sketched in Figure 2.1. The solid line represents the actual stage whereas the broken line gives the "effective" stage (= stage that would have occurred had the flow been unaffected by ice). At a certain time, which may be termed the beginning of freeze-up, the actual stage starts to rise while the effective stage continues to drop. Eventually, the actual stage attains a peak and then declines. This sequence reflects the dynamic nature of ice cover formation in rivers. With the onset of cold weather, frazil ice forms and is initially transported freely. The effect of this frazil ice on the water stage is small. As more and more frazil is produced, it begins to agglomerate into slush and pancakes. Eventually, the ice transport is impeded somewhere downstream of the gauge (due to border ice growth or other constricting features) and an ice cover begins to propagate upstream. The presence of the ice cover causes a local stage increase which eventually begins to be "felt" at the gauge site. The stage then increases until the time when the edge of the ice cover arrives at

the gauge site. Subsequently, the stage drops due to the combined effects of decreasing discharge and thermal smoothing of the underside of the cover. The peak stage (H_p) during this period is considered an important factor influencing the succeeding break-up because the width of the cover is approximately equal to the channel width at the stage H_p. To eliminate brief peaks during which there is little time for freezing, H_p is defined as a daily average value. It should be recognized that the above description may not apply in cases where there are severe flow and stage controls; where conditions are such that a complete ice cover does not form; where the discharge is decreasing so rapidly as to suppress the occurrence of a peak on the daily stage hydrograph; or where a precipitous stage drop occurs after the time of the peak so that the stable ice cover width cannot be represented by this peak[1]. Because these and possibly other uncertainties are not generally known beforehand, it is advisable to determine H_p in conjunction with the prevailing temperature and precipitation conditions as well as local observers' notes.

An example of an actual freeze-up stage record is given in Figure 2.2 where the wavy appearance is caused by upstream regulation. The record shows that ice effects began to be experienced at the gauge site in the early morning of November 15, 1972. This was followed by a sharp rise of 1.6 m by evening and a gradual decline afterwards. The calculated daily average stage hydrograph is, of course, much smoother than the instantaneous and shows a peak of 4.29 m on November 16. This value is thus taken as H_p which is also in agreement with the observer's report for November 16.

[1] For example, in some of the Mackenzie Delta channels, the flow is cut off by a drop of the main river stage, shortly after freeze-up. Consequently, the stable ice cover in these channels forms at a much lower stage than the original freeze-up peak (T.D. Prowse, personal communication).

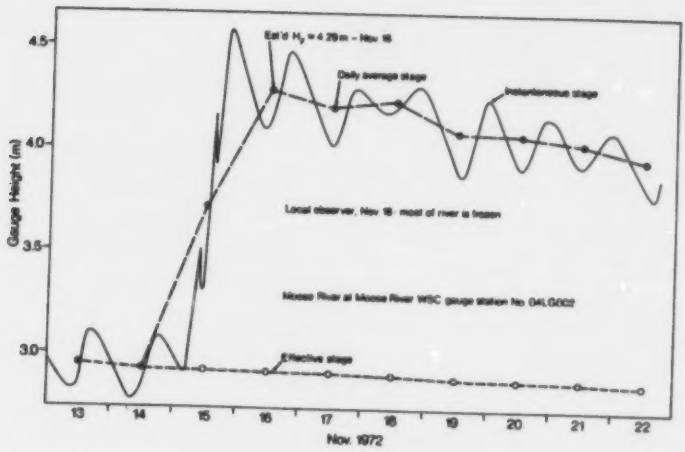

Figure 2.2. Freeze-up stage record, Moose River at Moose River

2.4.2. "Winter Peaks"

Occasionally, a brief thav may occur during the vinter period. If such a thav causes significant runoff, the gauge record will shov a peak which may or may not initiate break-up. In the latter case, the peak stage represents a lover limit for the stage required to initiate break-up at that time.

2.4.3. Stage at Initiation of Break-up (H_s)

Usually, when a thav does lead to break-up of the ice cover, the stage begins to rise from its fairly steady winter value and shortly after exhibits spikes and peaks that can only be caused by breaking or broken ice effects (Figure 2.3). A probable value of the stage at the initiation of break-up, H_s, may be fixed at the first significant spike. Unfortunately, this definition is not always objective or

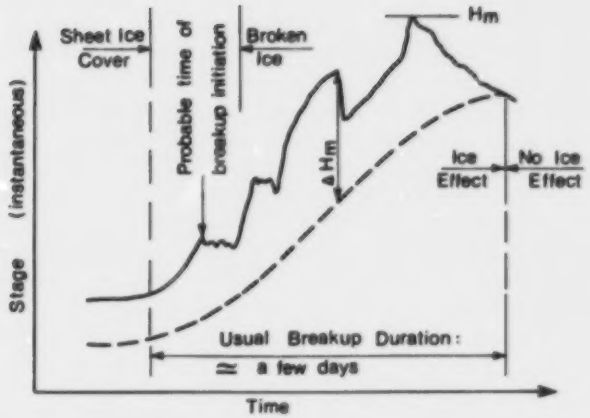

Figure 2.3. Schematic illustration of instantaneous stage variation with time during break-up

meaningful (see also later discussion)[1]. Only a probable range of H_o can then be determined, by considering: (a) the latest time for which it can be confidently assumed that there still was continuous ice cover; and (b) the earliest time for which broken ice effects became evident on the stage hydrograph. An illustration of actual break-up conditions is given in Figure 2.4. The water level is seen to rise during April 18, 1973, reaching a first peak of 4.42 m at 0600 on April 19. A sharp peak of 5.05 m occurred at about 1630 on April 19, followed by a quick drop of about 0.2 m and a renewed rise. The second peak is a more likely value for H_o because ice movement is usually associated with much steeper falling limbs than that of the first peak. This is confirmed by the local observer's report for April 19 and thus H_o is fixed at 5.05 m.

[1] Initiation of break-up is defined herein as the instant when a sustained movement of the ice cover begins. When the cover is set in motion, the resistance to flow is reduced and the stage should tend to drop, thus producing a spike on the stage hydrograph. Sometimes, however, the stage rise may be so steep as to suppress spike appearance. Only a slowdown in the rate of rise would then be evident.

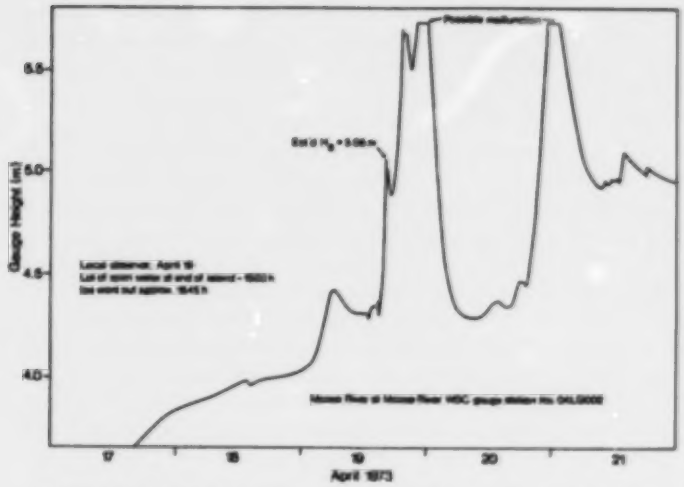

Figure 2.4. Break-up stage record, Moose River at Moose River

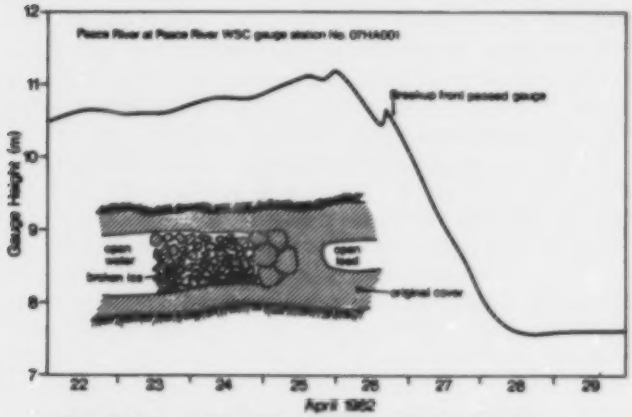

Figure 2.5. Stage record during overmature break-up (stage data taken from Ponstad, 1982)

However, identification of H_s may not always be as simple as indicated above, especially in cases where no local observations and reports are available. Particular difficulty would then be experienced in cases of:

i) Absence of spikes owing to very rapid increases in stage, caused by intense runoff or release of major ice jams upstream.

ii) "Misleading" spikes that may be caused by discharge reductions due to upstream jam formation or even disruption of the melt process.

iii) Overmature events where break-up can be initiated during constant or even dropping stage conditions. The ice cover would then be disintegrating gradually and our earlier definition of break-up initiation may not apply.

An example of overmature break-up is given in Figure 2.5, showing the stage hydrograph for the 1982 break-up period in the Peace River. Break-up was initiated near midnight of April 26 while the stage was generally decreasing (Fonstad, 1982). The wording "break-up front" refers to the configuration sketched in the inset of Figure 2.5: a relatively short accumulation of broken ice rests against the upstream edge of stationary sheet ice. Thermal and mechanical action causes the edge of the stationary ice to develop cracks while open leads form downstream. Eventually, the deterioration becomes so advanced that the broken ice is able to move into the leads where it comes to a temporary halt and the process is repeated. The fact that the broken ice accumulation does not lengthen with time implies that melting is one of the governing factors. Break-up initiation in this case can be defined as the passage of the "front", but it would be difficult to identify it on a stage recorder chart without local observers' reports. Moreover, the importance of H_s as an index of break-up initiation would probably be limited to its effect on flow velocity under the ice which, in turn, influences the rate of heat transfer from the water.

Because of the relatively little importance of the overmature break-up to ice jamming, the remainder of this report will concentrate on non-overmature break-up events. Before closing this

section, it is emphasised that the accuracy of H_s determinations would be greatly increased by availability of frequent local observers' reports during the break-up period (about 3-4 times a day); and by automatic recording of ice conditions via time-lapse photography or ice movement detection devices.

2.4.4. Maximum Break-up Stage (H_m)

This is the maximum stage reached during the break-up period and its determination is usually straightforward (see Figure 2.2). However, malfunctions caused by ice or other effects may cause problems. For example, Figure 2.4 shows two "suspiciously" flat and equal peaks near the respective midnights of April 19 and 20. In the absence of additional information, these peaks cannot be used as representative of H_m. It would thus seem highly desirable to instruct the local observer to identify the high water mark during each break-up event. During a subsequent visit of the gauge by operating agency staff, the high water mark could be surveyed.

2.4.5. Effective Stage and Maximum Ice Effect on Stage (ΔH_m)

The ice effect on stage is the difference between the actual stage and the effective stage. The time of maximum ice effect can usually be determined by simple inspection (Figure 2.3) and does not necessarily coincide with the time of H_m. Since the effective stage is obtained from discharge estimates as described in Section 2.3.3, ΔH_m values are subject to the same errors associated with discharge estimates during break-up. Examination of discharge measurement notes would enable subdivision of ΔH_m data into fair and uncertain ones. A more accurate indication of the ice effect on stage is the value obtained from a discharge measurement that happened to be performed during the break-up period. Such data should also be recorded for comparison purposes even though they do not generally represent the maximum ice effect, ΔH_m.

2.4.6. Ice Thickness (H_i)

Usually, a few ice thickness values will be available during any one winter season. These can be plotted versus time and an extrapolation can be made to the start of the mild weather spell that leads to break-up. Where the winter season involves highly variable weather conditions it may be preferable to extrapolate using a more complex correlation, e.g., h_i versus accumulated degree-days of frost. Such procedures would generally give fair indications of h_i at the time break-up starts but ignore thickness reductions that may occur during the pre-break-up period (onset of mild weather spell to onset of break-up). This assumption is considered adequate for the present in view of (a) the crudeness of the other data involved; and (b) the partial accounting of this effect by introducing a meteorological index of heat input to the ice cover.

2.4.7. Meteorological Index of Ice Strength

Few data on ice strength at the time of break-up are available and the manner of ice strength reduction by thermal effects is not well understood at present (Frankenstein, 1961; Korzhavin, 1971; Butyagin, 1972; Ashton, 1983). In general, it is reasonable to expect that ice strength will decrease with increasing amounts of heat absorbed by the ice cover but there is no consensus on the most appropriate index for the latter.

A very simple and well known index is the accumulated degree-days of thaw, S_T (see for example, Williams, 1965; Bilello, 1980). It is clear, however, that S_T can only be satisfactory in cases when the time of year at which break-up occurs and the number of "thawing" days do not vary appreciably. Otherwise, the important effect of solar radiation will not be considered. For example, a sunny day in April would be much more effective in weakening the ice than a cloudy day of the same average air temperature in January. It is evident that, to fully account for thermal effects on ice strength, several parameters are needed in addition to air temperature, e.g., short-wave radiation, cloudiness, wind speed, water temperature, snow cover, ice composition, etc.

Unfortunately, not all of this information is usually available and even if it were, it would be impractical to attempt multiple correlations with so many parameters. Shulyakovskii (1966) suggested the use of a calculated value of heat input to the ice cover from the surface, thus ignoring heat transfer from the water since water temperature is, as a rule, unknown. A similar but somewhat simplified approach was suggested by Williams (1965). Bulatov (1972) outlined a method for computing ice strength based on theoretical and experimental correlations with radiation effects. However, Bulatov's paper was too general to permit application of his method by others. Ashton's (1983) analysis is similar to Bulatov's and shows that the main agent of deterioration is the penetrating solar radiation, once the ice has been warmed to 0°C. Additional radiation absorption causes melting at the grain boundaries with a resulting decrease in strength. However, Ashton's analysis cannot be applied to the data under consideration because information on snow cover, albedo and ice structure is lacking.

Evidently, only empirical indices of ice strength can be employed at present. Some of the simplest ones are accumulated degree-days of thaw, hours of sunshine and solar radiation but their simultaneous consideration would complicate the analysis. Shulyakovskii's (1966) single heat input parameter, Σq, has the advantage of simplicity as well as a history of practical usage. However, there is no theoretical evidence that this parameter adequately accounts for the qualitatively different effects on ice strength of the various heat components involved. A possible means of resolving this question is to perform a few comparative studies, i.e., to compare the forecasting effectiveness of Σq versus that of other indices such as accumulated degree-days, hours of sunshine, solar radiation, etc.

2.5. DISCUSSION

At present no definite rules can be offered for interpreting data gathered according to the previous section because it is still too early to confidently adopt a general interpretation methodology.

A partial illustration of data interpretation is given in the Appendix where a case study on the Nashwaak River, New Brunswick, is

described. This study (Beltaos and Lane, 1982) utilizes some of Shulyakovskii's (1966) suggestions along with a more recent understanding of ice jams. The main findings of the study[3] are broadly as follows:

i) Forecasting the time of break-up initiation. The corresponding stage H_s is a suitable index while the difference $(H_s - H_r)$ is related to h_i and a measure of thermal ice deterioration. For the latter, several indices have been used in the past but there is no consensus on which is the optimum. For the Nashvaak River study, Shulyakovskii's heat input parameter was used and gave fair correlations. The effects of channel geomorphology (fixed for a given site) are unknown at present; they can only be investigated by comparison of several site-specific case studies.

ii) Forecasting the severity of break-up. The peak break-up stage, H_m, is known to be influenced by discharge while preliminary information suggests that H_r, h_i and thermal deterioration may play a role. The effects of channel geomorphology are partly understood via the theory of equilibrium jams. At present, only upper bounds of, or potential, H_m values can be forecast. Actual H_m predictions are not possible.

iii) Frequency of H_m. This can be done simply by ranking H_m values and computing corresponding probabilities. Use of H_m', a value reduced by the stage of zero discharge, is convenient. Preliminary indications are that H_m' may adhere to the log-normal distribution which can be defined by specification of two parameters. Comparison of several case studies might result in correlations of these parameters with geomorphic and basin characteristics.

Earlier considerations have highlighted several instances where relatively modest increases in the effort associated with the operation of a gauge, would result in very important contributions toward development of forecasting methods, specifically:

[3] and also of several similar case studies at other gauge sites (Beltaos, unpublished data). None of these studies includes overmature break-up events.

- Accurate ice thickness values can be obtained by recording the distance of the water level to the top of the ice cover and the solid versus slush ice fractions where applicable.
- The accuracy of H_r and (more importantly) H_s determinations would be greatly enhanced by increasing the frequency of the local observer's reports to three or four times a day during freeze-up and break-up. Ice movement detection devices, time-lapse photography or simply occasional photographs would also be helpful.
- At some locations, broken ice causes the gauge to malfunction so the H_m values are, as a rule, missing. Identification of the high water mark during break-up by the local observer would enable later survey and determination of H_m. In doing this, care should be exercized to ensure that H_m applies to ice-influenced flow conditions and not merely to open-water flow.

2.6 GUIDELINES

The procedures for performing a break-up case study are summarized in this section.

2.6.1. Selection of Gauge Site

The following criteria should be examined prior to selection:

i) A significant ice cover (thicker than about 10 cm) forms in the vicinity of the gauge location during most winters.

ii) The length of record is adequate, i.e., more than about 15 years.

iii) Water level recorder malfunctions during break-up are rare.

iv) River geometry has not been subjected to significant changes during the length of record. One indication regarding this aspect is the stability of the gauge rating curve.

v) Accessibility of gauge site and vicinity. It may eventually be desired by users to survey a few cross-sections and even perform *in situ* ice observations as a supplement to data interpretation.

vi) Availability of local observer's reports.

vii) Discharge measurements under ice-covered conditions are, as a rule, carried out. Associated ice thickness indications are

representative of the solid ice layer, i.e., no major slush accumulations.

viii) Discharge estimates during break-up are relatively accurate owing to favourable conditions, e.g., timely measurements, upstream and downstream gauges where ice break-up was completed earlier, etc.

ix) Proximity of representative meteorological station(s).

x) Consideration should be given to study sites where snow run-off prediction models such as SSARR are already in place. Here a possibility exists to relate the defined snow conditions to the strength of the ice cover with respect to break-up.

2.6.2. Descriptive Information on Ice Regime

An overall qualitative description of the ice regime in the vicinity of the gauging station would be helpful in break-up data interpretation. Presentation of, or reference to, the following information is recommended.

i) River profiles and plan view of river obtained from 1:50,000 maps, flood plain maps and/or other existing water resource reports on the river.

ii) Monthly and daily discharge characteristics of the river (mean, maximum and minimum of record).

iii) Statistical meteorological conditions at the site described in Canadian and Provincial climatological atlases.

iv) Satellite photos taken at regular intervals over the winter. These photos are particularly useful for large rivers where formation and progression of the ice cover is relatively slow. The open water zones can be clearly distinguished from the ice covered portions of the river in the absence of cloud cover.

v) Interviews with local residents are optional but are highly recommended for more detailed studies.

2.6.3. Data Processing

For each season, the following items are needed:

i) Identify approximate period of ice cover. If there are more

than one ice cover periods, identify and process each one separately.

ii) Identify and record time and value of H_y. Consult -- recorder chart; daily average stage table; local observer's reports; and weather conditions.

iii) Inspect recorder chart after the time of H_y. Identify significant winter peaks and record their times and values.

iv) Roughly locate the break-up period on the chart, i.e., start of final rise of water level to end of ice effect. Drav the effective stage graph by joining with a smooth line daily average values plotted at noon of corresponding days. Effective stage can be found from estimated discharge via the gauge rating curve or table. Consult weather conditions and local observer's reports and make notes where appropriate. Identify and record times and values of H_s, H_m and stage corresponding to ΔH_m, along with applicable discharges. If H_s can only be identified as a range, record parameters pertaining to the limits of the range.

v) Examine applicable discharge measurement notes. Compute average nominal "ice thickness" and divide by 0.96 to find h_i. Interpolate or extrapolate to determine h_is that apply to winter peaks and to H_s. Note whether any discharge measurements were made after the time of H_s and before the end of break-up. This would give an indication of the accuracy of discharge and effective stage determinations corresponding to H_m and ΔH_m.

vi) Tabulate pertinent information, including remarks on the accuracy or uncertainty associated with each value.

2.6.4. Interpretation

No specific rules for interpretation of the data gathered during the processing phase can be formulated at present. Initially, much will depend on the user's ovn ideas as well as on the type of break-up processes involved, e.g., premature, overmature or intermediate events. A fev possibilities are illustrated and discussed elsevhere in this report while it is reasonable to expect that interpretation

methods will be continuously updated as understanding increases.

2.6.5. Presentation of Data

When processing is completed, it would be desirable to issue a summary report. Such reports could then be utilized by various users either for research or site-specific forecasting purposes. It is envisaged that a typical report would include the following information:

i) Brief description of gauge site and ice regime, as outlined in Section 2.6.2, or indications as to where and how this information could be obtained by the user.

ii) Stage-discharge relation (open-water).

iii) Tables summarizing data on each freeze-up/break-up sequence, i.e., H_f, H_s and times of their occurrence; summaries of discharge measurements performed during the sequence -- include date, discharge, ice thickness and stage; H_m, ΔH_m and times of their occurrence, along with prevailing discharges -- indicate the reliability of the discharge values. As an example, the summary form used by the writer is shown in Table 2.1.

iv) Data interpretation (optional).

v) Appendices including copies of recorder charts during the freeze-up and break-up events; local observer's notes; discharge measurement notes; and applicable meteorological records (optional) -- include temperature, precipitation and bright sunshine.

2.7 SUMMARY AND CONCLUSIONS

A major need for field data pertaining to various aspects of river ice break-up and jamming has been identified. While indications are that ice monitoring activities in Canada will increase in the future, it was suggested that considerable benefits can be derived from exploitation of existing data sources and specifically hydrometric gauge records. Guidelines for extracting pertinent information from such records were presented and associated limitations discussed. Methods for interpreting this information as a means of developing

Table 2.1. EXAMPLE OF DATA SUMMARY FORM

Gauge Site _____
Event No. ____ of ____. Processed by _____ Season _____
on _____

Begin Ice Effect on Stage at _____ h on _____
Stage = _____ m. Discharge = Q = _____ m^3/s.

H_r = _____ m on _____

"WINTER" PEAKS

H_p> (m)	TIME/DATE	H_i (cm)	M/E [1]	ST (°C-days)	Σq (J/cm^2)	(other)

DISCHARGE MEASUREMENTS

TIME/DATE	Q (m^3/s)	STAGE (m)	EFFECTIVE STAGE (m)	h_i (cm)	ICE CONDITIONS

BEGIN RISE TO BREAK-UP AT _____ h ON _____
STAGE = _____ m. DISCHARGE = Q = _____ m^3/s.

H_b (m)	TIME/DATE	h_i (cm)	M/E [1]	ST (°C-days)	Σq (J/cm^2)	(other)

H_m (m)	TIME/DATE	Q (m^3/s)	ΔH_m (m)	TIME/DATE	STAGE (m)	Q (m^3/s)

REMARKS ON RELIABILITY OF H_r, H_b, H_m AND Q VALUES:

([1]) Use M for h_i determinations based on interpolations or extrapolations of one or more measurements; use E for estimates based on other years' experience.

related forecasting procedures were illustrated by means of a case study. At the same time it was shown that no universal interpretation rules can be formulated at present. To improve this situation, many more case studies are needed. In turn, this task can be greatly facilitated by the participation of operating agencies in, at least, the data extraction phase from the hydrometric gauge records. Preparation and issue of pertinent reports with or without the interpretation phase is strongly recommended. Discussion of data extraction methods revealed several instances where modest increases of the gauge operation effort would result in substantial improvement of the accuracy and utility of the records for ice-related applications.

2.8. ACKNOWLEDGEMENTS

Much of the work discussed herein has been a part of a long-term study initiated in 1979 by the Environmental Hydraulics Section, Hydraulics Division, National Water Research Institute, in cooperation with the Guelph Office of the Water Survey of Canada. The Nashwaak River example was carried out jointly with the Fredericton Office of the Water Survey of Canada, partly under the auspices of the N.B. Sub-Committee on River Ice. Comprehensive reviews and many valuable comments contributed by members of the NRCC Working Group on River Ice Jams are gratefully acknowledged. Reviews by Dr. T.M. Dick and Dr. Y.L. Lau are appreciated.

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APPENDIX 2.A. - EXAMPLE OF DATA INTERPRETATION

This example is based on the Nashwaak River case study of Beltaos and Lane (1982). The study area is shown in Figure 2.6. Details of data extraction and interpretation are given in Beltaos and Lane (1982) while Table 2.2 summarizes selected parameters extracted from the records.

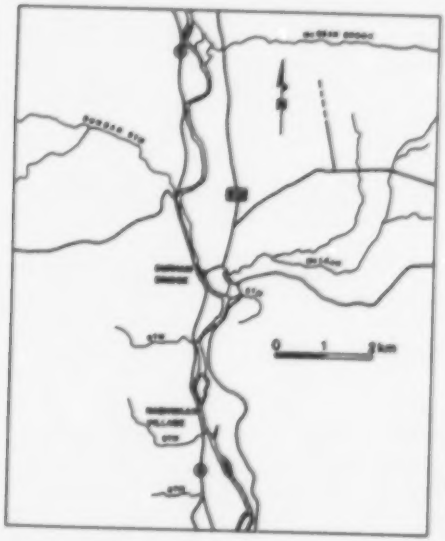

Figure 2.6.

Plan view of Nashwaak River near Durham Bridge

Initiation of Break-up

The data interpretation has followed Shulyakovskii (1963), after some initial verifications of the basic premises. First, H_b was plotted versus H_f, where a trend for H_b to increase with H_f was indicated. However, there was considerable scatter suggesting additional effects. Next, the difference (H_b - H_f) was postulated to depend on h_i and Σq, the total amount of heat input to the ice cover per unit surface area. The latter is an accumulation of daily average heat fluxes (q) until the time of break-up initiation; heat transfer from

Season	H_T (m)	Time of H_T (day/month)	Winter Peaks: H (m)	Winter Peaks: Time of H	Winter Peaks: Eq (J/cm²)	Break-up: Range of H_B (m)	Break-up: Probable H_B	Break-up: Time of H_B	Break-up: Eq (J/cm²)	Break-up: Eq Calculated to (day/mo.)	Ice Thickness: h_i	Ice Thickness: Time of Measurement	Maximum Stage: H_B (m)	Maximum Stage: Time of H_B	Maximum Stage: Discharge H_B (m^3/s)	Maximum Ice Effect: ΔH_B (m)	Maximum Ice Effect: Time of ΔH_B	Maximum Ice Effect: H (m)	Maximum Ice Effect: Discharge (m^3/s)	Remarks
1964–65	2.56	13/1	2.20	7/3	2263															Break-up indefinable
1965–66	1.40	29/12					1.58	22/3	2807	22/3			2.23	26/3	83	0.55	22/3	1.58	22	
1966–67	1.80	27/12					1.71	7/4	5992	7/4	0.70	16/3	1.73	11/4	15	0.82	11/4	1.73	15	
1967–68	2.34	1/1					3.25	4/2	461	4/2	0.37	12/1	3.87	4/2	100	2.05	4/2	3.87	100	h_i not representative of break-up value
1967–68	3.35	6/2	2.78	25/3	3655		2.71	30/3	6411	30/3			3.40	1/4	93	1.65	1/4	3.40	93	
1968–69	2.25	29/12	1.84	27/1	0		1.87	28/3	3562	28/3			1.87	30/3	22	0.82	30/3	1.87	22	Difficult to define break-up
																5.31	4/2	697	0.92	4/2	5.31	697	– " –
1969–70	3.44	1/1				1.98–5.31		2–4/2	587	3/2						2.05	28/3	34	0.82	28/3	2.05	34	– " –
1969–70	2.29	16/2				1.43–1.80		27/3	6819	27/3													
1970–71	1.65	10/12	2.07	15/2	251	0.90–131		3–4/4	6872	3/4	0.64	11/3	1.96	14/4	49	0.93	6/4	1.79	30	
			1.83	14/3	2179				7542	4/4										
1971–72	1.19	7/12	1.34	13/12	251	1.62–21.9		17–19/3	1046	17/3	0.73	6/3	2.49	20/3	28	1.39	20/3	2.49	28	
			1.63	16/1	0															
			1.59	16/2	1343															
			1.74	12/3	0															
1972–73	2.72	14/12	2.79	5/2	0	1.91–2.35		17–18/3	5363	18/3			2.61	19/3	76	1.27	18/3	2.53	40	
			2.16	13/3	3352															
1973–74	2.20	10/1	2.22	6/3	3017	1.56–2.19		4–7/4	2682	4/4	0.70	27/3	2.19	7/4	56	0.76	7/4	2.19	56	
									4735	7/4										
1974–75	2.19	4/1	2.15	22/3	2137	1.40–1.68		4–8/4	4483	4/4			1.68	8/4	32	0.52	8/4	1.68	32	Difficult to define break-up
									6034	8/4										
1975–76	2.44	14/12	3.38	29/1	277		2.19	27/3	4864	26±27/3(avg)	0.73	2/3	2.94	29/3	126	1.15	30/3	2.78	126	
1976–77	1.89	12/12	2.69	27/12	0	1.49–1.53		27–28/3	6411	27/3			2.29	31/3	74	0.69	31/3	2.29	74	Difficult to define H_B and H_T; H_T = 2.29 on 29/12 might be better
			1.91	16/3	3645															
																2.51	26/12	42	1.23	26/12	2.51	42	Probably thin ice
1977–78	1.82	11/12				2.15–2.51		26/12	21	26/12						1.76	15/4	47	0.44	15/4	1.76	47	Difficult to define H_T
1977–78	2.74	18/1				1.42–1.54		11/4	7123	11/4													
																2.57	3/1	74	0.96	3/1	2.57	74	
1978–79	1.10	27/11				< 1.93		3/1	283	2/1						3.20	26/3	207	1.15	15/3	2.76	74	Difficult to define break-up
1978–79	3.40	7/1	3.26	31/1	1049	1.54–2.65		5–6/3	922	5/3										
									2179	7/3										
1979–80	2.25	6/1				2.71–3.01		18–19/3	629	18/3	0.55	13/3	3.03	19/3	105	1.65	1/4	2.84	36	
1980–81	2.41	17/12				1.81–2.11		19–23/2	712	18/2			2.12	23/2	66	0.57	23/2	2.12	66	
									2556	22/2										

TABLE 2.2. SUMMARY OF BREAK-UP CHARACTERISTICS AND ASSOCIATED PARAMETERS; NASHVAAK RIVER AT DURHAM BRIDGE 1965–81

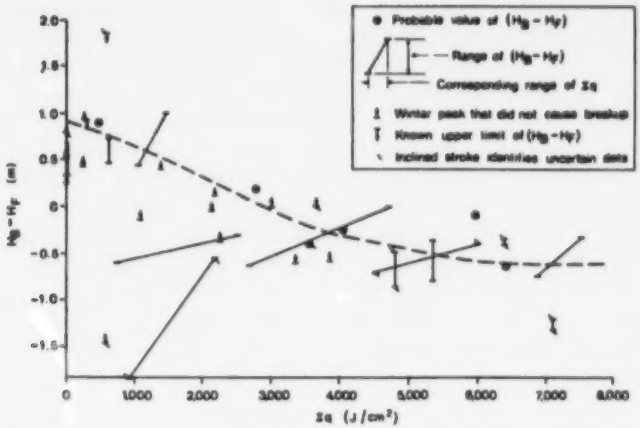

Figure 2.7. Stage rise above H_y required to initiate break-up, as a function of Σq

the water is ignored. Calculation of Σq involves several simplifying assumptions so that Σq must be viewed as a mere index of the true amount of absorbed heat.

At the time of preparing the report (Beltaos and Lane, 1982) very little information on h_i was available, hence $(H_s - H_y)$ was plotted versus Σq, as shown in Figure 2.7. The scatter is large but the data points appear to follow the anticipated trend. Later, additional ice thickness data were made available to the writer by P. Tang of N.B. Environment which enabled a two-parameter correlation[4] as follows. First, $(H_s - H_y)$ was plotted versus h_i by noting the value of Σq beside each data point. This indicated both an increase of $(H_s - H_y)$ with h_i and a decrease with Σq. The upper envelope of the data points, assumed representative of the case Σq = 0, could be described

[4] There still remained a few years without any ice thickness measurements. For these years, h_i was estimated using a correlation of measured h_i versus time from H_y. This procedure could involve errors as large as ±30%. Water surface to bottom of ice distances quoted by the WSC have been divided by 0.92 to obtain h_i though this is recognized to be a crude approximation.

by the straight line $H_s - H_y = 2.5\ h_i$. Next, the deviation of any one data point from the upper envelope [$= 2.5\ h_i - (H_s - H_y)$] was computed and plotted versus Σq, as shown in Figure 2.8. The latter seems to be an improvement over Figure 2.7; the scatter is reduced while only one event, associated with uncertain record interpretation, does not fit the general trend[3]. The scatter in Figure 2.8 is still fairly large and this could be partly attributed to: (a) the crudeness of H_s determinations -- no local observer's reports were available; and (b) the empiricism utilised in arriving at the final parameter that is plotted versus Σq -- lack of a theoretical framework of break-up processes. A favourable circumstance is that even a large error in predicting H_s usually translates to acceptable error in predicting the time of break-up initiation because the corresponding stage gradients with respect to time are large.

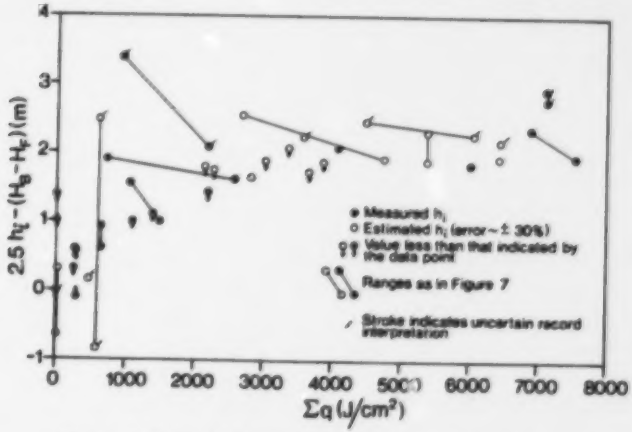

Figure 2.8. Variation of $2.5\ h_i - (H_s - H_y)$ with Σq

[3] Since writing this report, it was discovered that this event had been interpreted incorrectly, being a winter peak rather than a break-up event. The actual break-up occurred later in that season and plots at a much improved position (e.g., see Beltaos, 1984).

Maximum Break-up Stage

As discussed earlier, flow discharge is a major factor influencing H_m. However, discharge data for the Mashvaak River study are uncertain so that the plot of Figure 2.9, showing H_m' (= H_m -- stage at zero discharge) versus prevailing discharge is merely of qualitative value. It is noted that some of the data points in Figure 2.9 represent conditions of maximum ice effect, ΔH_m, in instances where the latter did not coincide with H_m. Also plotted in Figure 2.9 is the theoretical relationship between equilibrium jam

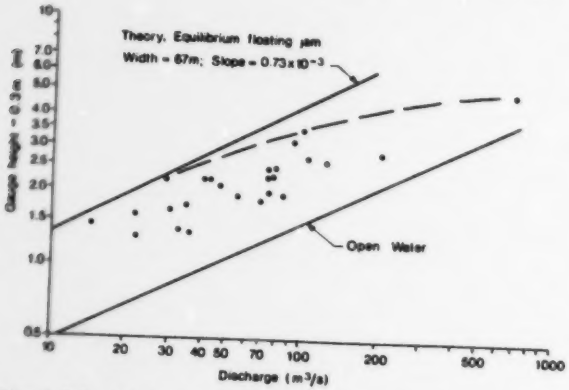

Figure 2.9. Effect of discharge on stage during break-up

stage and discharge for comparison (Beltaos, 1983a). The latter is seen to provide a satisfactory upper envelope up to a certain discharge, but consistently to overpredict the stage beyond this discharge. This is a typical trend, reflecting the fact that increasing discharge reduces the probability of equilibrium jam formation (Beltaos, 1983a). For practical purposes, an upper envelope of the data points could be drawn and used to forecast potential H_m values. Whether and how closely the potential H_m is to be realised in a given season depends on the number and stability of ice jams that form near the gauge site, as discussed earlier. In turn, such effects are controlled by channel and floodplain

configuration as well as the competence of the ice cover during break-up. The former factor is difficult to assess at present because the behaviour of ice jams is unknown once the bankfull stage is exceeded (see also Calkins, 1983). On the other hand, experience suggests that the competence of an ice cover should be an important factor influencing H_m and this possibility will be considered next.

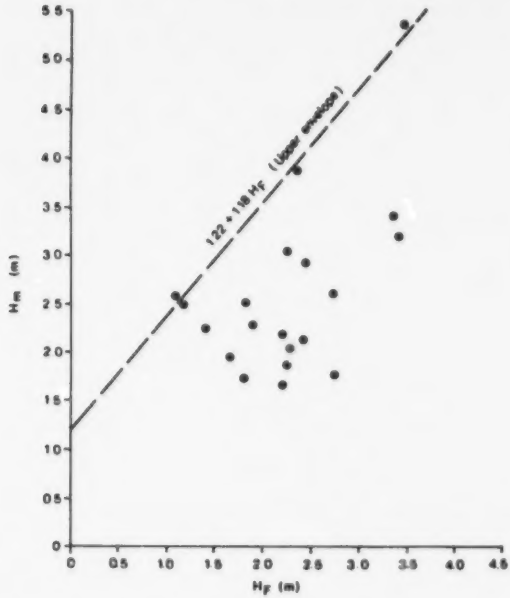

Figure 2.10. Maximum stage during break-up versus HF

Since the competence of an ice cover can be defined in terms of its strength, thickness and width, it may be of interest to explore Σq, h_i and H_F (rough measure of ice cover width) as possible factors influencing H_m. Figure 2.10 shows H_m plotted versus H_F. The data points define an upper envelope which increases with H_F. The deviation of the observed value of H_m from the corresponding upper envelope value is plotted versus Σq in Figure 2.11. This results in

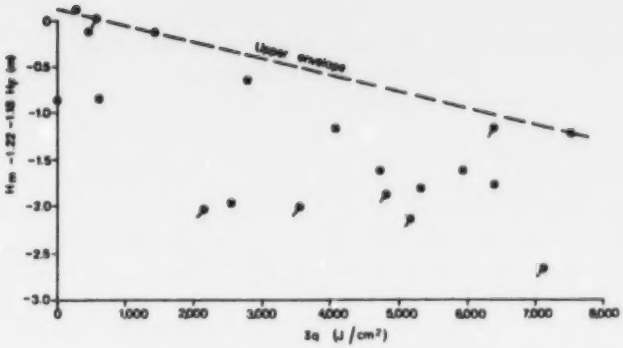

Figure 2.11. Effect of Iq on H_m

another upper envelope which confirms the anticipated trend. It thus appears that H_r and Iq define an upper limit for, or potential, H_m[4]. Whether and how closely this potential will be realised in any one break-up event, depends on a number of other factors, e.g., discharge, local jamming conditions, etc.

Frequency of Occurrence of H_m

A simple frequency analysis on H_m values was also performed using the following equation (Gerard and Karpuk, 1979):

$$P = (m - \frac{3}{8})/(N + \frac{1}{4}) \qquad (1)$$

in which P = probability of a given stage being equalled or exceeded during any one break-up event; m = rank; and N = total number of analysed break-up events. The fact that, occasionally, there have

---

[4] (1) One would expect that h_i should also be relevant here but this possibility has not been investigated in this example. Effects of freeze-up conditions and h_i on H_m have also been discerned at other sites (British Columbia Hydro, 1975; Beltaos, 1983b).

(2) Strictly speaking, Iq should be calculated to the time of H_m. However, the value used in Figure 2.5 applies to the time of H_r. This was thought sufficient given that the Nashvaak River study was exploratory. Nevertheless, both these elaborations should be kept in mind for future work.

been two break-up events in the same season has been ignored and all events have been assumed to be independent so as to increase the value of N. This may or may not be valid but more data are required to clarify this point.

For convenience of plotting, the gauge height has been reduced by H_o, the value corresponding to zero discharge, i.e., use has been made of $H_m' = H_m - H_o$. In this manner, the event $H_m' \geq 0$ has a probability P = 1. After performing the frequency analysis, H_m' can be plotted versus P on various types of probability charts as a means of exploring the mathematical form of the H_m' distribution. Gerard and Karpuk (1979) suggested that the log-normal distribution is a possible candidate in this respect and found a linear relationship on plotting their data on log-normal probability paper. The Nashvaak River data are compared with Gerard and Karpuk's Peace River data in Figure 2.12 where the ratio $H_m'/H_m'_{50}$ is plotted versus P. Note that $H_m'_{50} = H_m'$ at P = 0.5. Figure 2.12 shows that a linear fit could only partly describe the Nashvaak River results. It is also noted that there is a near coincidence with the Peace River data in the linear range ($0.1 \leq P \leq 0.90$) but the reason for this is not known.

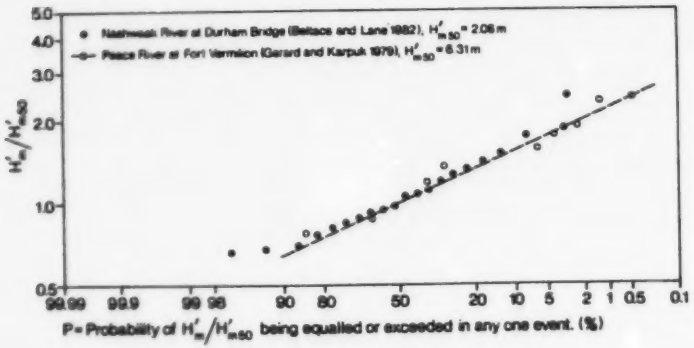

Figure 2.12. Results of probability analysis

Limitation

Beltaos and Lane (1982) emphasised that the Nashvaak River study was purely empirical and site-specific. Thus, extrapolation of their findings to other sites or to meteorological conditions not representative of the range covered by the years of record, would not be justifiable. Clearly, a generalization of forecasting methods on river ice break-up requires many more case studies of this kind. Only then would it become possible to examine additional effects such as stream geomorphology, basin characteristics and climatic conditions.

Example of Application

Suppose that, in a given season, H_y = 2.50 m. On March 14, a warm weather trend and increased runoff are forecast for the next few days, as indicated below:

	Date in March	Mean Daily Air Temperature (°C)	Hours of Sunshine	Gauge Height (m)	Discharge (m^3/s)
Known	13	-5	0	1.52	33
	14	-2	4	1.52	33
Forecast	15	2	5	1.83	48
	16	4	8	2.44	86
	17	6	10	3.35	155
	18	Turning Cold			<155

From previous ice thickness measurements h_i is fixed at 0.40 m. To calculate Σq, we can use the following equation (Beltaos and Lane, 1982)

$$q = a\theta + bS_u + c \qquad (2)$$

in which q = daily amount of heat (J/cm^2); θ = daily average air temperature (°C); S_u = hours of bright sunshine; and a, b, c are coefficients which depend on latitude and time of year. For the Nashvaak River at Durham Bridge at about mid-March, the values of a, b and c are 68.7, 26.8 and 160.1, respectively. With these, we compute q = negative on March 13; and q = 130, 432, 649 and 840 for

the subsequent four days. Correspondingly, values of Σq and H_s (via Figure 2.8) are as follows:

Date in March	Σq (J/cm²)	H_s (m)	Gauge Height (m)
13	nil	3.50	1.52
14	130	3.40	1.52
15	562	2.97	1.83
16	1211	2.46	2.44
17	2051	2.05	3.35

Assuming that the above values apply at about noon of each day, break-up is expected to start sometime on March 16, this being the first date on which H_s will become less than the expected gauge height. The corresponding value of Σq is 1211 J/cm². Figure 2.11 then gives H_m - 1.22 - 1.88 $H_r \leq$ -0.10 m. It follows that H_m should not exceed 4.1 m. If the peak instantaneous discharge is assumed to be equal to 155 m³/s, then Figure 2.9 would give $H_m \leq 4.4$ m, so that the former limit (4.1 m) would apply. If, on the other hand, the discharge were to peak at, say, 80 m³/s, Figure 2.9 would give $H_m \leq$ 3.7 m and this could be taken as the applicable limit of H_m.

Chapter 3. ICE JAM RESEARCH NEEDS

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3.1. INTRODUCTION

An ice jam has been defined by Gerard (1984) as "a forced accumulation of ice fragments in a waterway". This definition has been used as a guide herein -- in particular it excludes consideration of hanging dams and ice dams.

Ice jams are an integral part of both freeze-up and break-up on a river. They can also cause considerable difficulties for man's activities, such as sudden disastrous flooding. The more important impacts of ice jams are described and illustrated in Gerard (1984). Suffice it to say here that in recent years there has developed an increased awareness of the significant role of ice jams in hydrotechnical engineering in cold regions, and of the need to understand and consider them.

The current understanding of the phenomenon is poor and there is an urgent need to improve it. Of all countries, outside the U.S.S.R., Canada has the largest vested interest in understanding ice jams and should obviously play a leading role in the required research. To provide some guidance in mounting this research, suggestions made by the NRCC Working Group on Ice Jams as to the most important aspects of ice jams, and the needed research, are presented in what follows. Because of space limitations and the terms of reference of the Working Group, the discussion is confined to ice jams themselves, and does not consider the plethora of research needs on other aspects of river ice regimes. It is also not a review of the literature on the subject. Such reviews have been provided by Ashton (1986), Davar (1977) and others. Nor is it intended to be exhaustive. Instead the aim has been to highlight what are perceived by the Working Group to be the outstanding problems and to point out that, although there is a common perception that a lot of ice jam research has been done and there is little more of practical value to

be learned, this is far from the truth. In fact, the battle for a true, and practical understanding of ice jams has hardly been started.

Ice jams occur both at freeze-up and break-up. While there are obvious similarities in the jams formed in the two circumstances, there are sufficient differences to make it worthwhile treating them separately. Those features they have in common that require research will only be mentioned once.

3.2. FREEZE-UP ICE JAMS

On most rivers the formation of an ice jam is a necessary precursor to the development of an ice cover. As cold weather continues the water cools to 0°C, frazil ice begins to form and accumulate on the surface, and shorefast ice grows out from shore. Eventually, at some point along the stream, the width between the edges of the shorefast ice is small enough, and the concentration of floating frazil ice is high enough, to cause the frazil pans or slush to lodge, or jam, between the shorefast ice. Thereafter frazil moving down the stream accumulates upstream of this lodgement site and an ice jam develops, forming the initial ice cover on the stream.

3.2.1. Lodgement

This is possibly the most important feature of freeze-up jams, both because it is responsible for initial ice cover formation and because it is likely very sensitive to a change in flow regime, such as that which accompanies dam construction. Yet it is a feature about which little is known. Lodging of frazil between shorefast ice obviously depends on channel geometry, frazil concentration and form, open water width, flow and meteorological conditions. A typical situation just prior to lodgement is shown in Figure 3.1.

The most pressing need is for systematic documentation of such field situations to define, or at least place bounds on, the conditions necessary for lodgement. Laboratory and analytical studies of the interaction between slush, pans and floes in such constrictions could provide useful supplementary information on the important processes involved. Most work to date has involved laboratory

studies of the limitations to passage or entrainment of solid ice floes at contractions. Although the primary application of such studies is to lodgement at freeze-up, this application is limited because of the neglect of the frail nature of frazil slush and pans and their mechanical properties under various meteorological conditions.

Figure 3.1.

Looking downstream over frazil pans moving through surface contractions caused by shorefast ice.

3.2.2. Accumulation Progression

Following lodgement, the ice moving down from upstream accumulates behind the lodged ice if the velocity is not too high. The nature of this accumulation depends strongly on its bulk compressive strength, the effect of the flow under the accumulation, and the velocity required for entrainment of the approaching frazil ice at the head of the accumulation and for its subsequent deposition.

Because they provide indirect indications of the above parameters, the need is for field measurements of the character of accumulations in such freeze-up jams, such as the accumulation thickness, porosity and roughness along the jam; the manner of

development of the accumulation, such as the geometry of the head of the accumulation, and the packing and shoving of the ice in the accumulation; degree of refreezing and so on. Direct measurements of these features will obviously be easier in small streams but, because of the simpler analytical situation, measurements on large streams are also necessary. In addition to direct measurements, some of the above features can be deduced indirectly, at least approximately, from simple measurement and analysis of the water surface profile. Again, a valuable supplement to these field measurements would be laboratory studies of the fundamentals of the processes involved (as against physical models of given situations). Such investigations may or may not use ice. For example, much of the current understanding of ice jam processes came from early work on log jams using wood pieces in the laboratory. One very important feature of accumulation strength -- the effect of a thin refrozen layer -- could most usefully be studied in the laboratory. Other features that could be studied in the laboratory are the hydraulics of shallow flow beneath such rough accumulations, the erosion and deposition of frazil in its various forms moving under an accumulation, the possibility of thickening of the accumulation by shoving causing the accumulation to ground and, indeed, the effect of features of a non-prismatic channel on development of the accumulation in general. As usual, such field and laboratory studies will benefit from the development and application of related analytical models, either theoretical or empirical, to summarize the findings.

3.2.3. Hydraulics

Mention was made above of the need for study of the hydraulics of flow under ice jam accumulations. Progression of the accumulation causes the flow to be unsteady. There is likely to be a strong interaction between accumulation development, the water profile and the flow distribution along the accumulation. The current understanding is only of accumulation development under a steady approach flow. Very little is known, for example, of how a developing accumulation adjusts with an unsteady inflow, particularly if this approach flow is subject to sudden and significant changes such as

might be expected downstream of a peaking hydroelectric plant.

3.3. BREAK-UP ICE JAMS

Ice jam initiation at break-up is usually quite different from that at freeze-up. It is felt that break-up of an ice cover while it is still competent can only be accomplished by surges released by ice jam failure, and that most major break-up ice jams are simply the result of stalling of the break-up front at a resistant portion of ice or at a location, such as the head of a reservoir, that has a normal ice cover but has an expanding channel geometry that weakens the impetus of the surge. Hence, no 'lodgement' is generally involved for a break-up jam, the existing solid ice cover providing sufficient 'key' for the jam; the accumulation forms more rapidly and under much more unsteady circumstances; and the accumulation consists of a cohesionless collection of sizeable strong chunks of ice, without the refreezing complication present at freeze-up.

3.3.1. Jam Initiation

As for freeze-up, the major, yet least understood feature is jam initiation. As mentioned, this usually involves the stall of a break-up front against a resistant solid ice cover rather than the lodgement mechanism characteristic of freeze-up jams. Initiation of a break-up jam, therefore, has more to do with the formation of these resistant portions of the ice cover, and with the characteristics of the surge that is responsible for break-up, than with the passage of fragmented ice through various constrictions or with the floe entrainment that has been the focus of research on ice jam initiation in the past.

A major need is observation of break-up progression in the field over long reaches, the identification of the major ice jams, and the reasons for their formation. A related item is to determine how strong an ice sheet needs to be to stall break-up in various circumstances. This should be amenable to laboratory study, although it will require development of appropriate scaling laws and use of a model 'ice' that correctly scales the salient mechanical properties of the ice cover (e.g., see Ashton, 1986).

3.3.2. Jam Development

There is evidence that break-up jams develop in a variety of ways. The most elementary, but perhaps the rarest as far as severe jams are concerned, is the quasi-steady accumulation of single-layer floes moving downstream on a more or less steady flow, as usually occurs at freeze-up. The other, and probably more common, situation is the arrival of a "slug" of ice -- more the cessation of a moving ice jam -- in the presence of very unsteady flow. There has been no published investigation of whether jams formed under such circumstances would take up a geometry similar to that usually assumed. The formation of thicker, and sometimes grounded accumulations would seem likely under such circumstances. Simple laboratory experiments using simulated ice fragments, and perhaps some theoretical analysis, should provide valuable information on this possibility. As they become available, field observations will better define the range of circumstances under which ice jams form and the appropriate initial conditions so that such laboratory and analytical studies can define the limits of the current quasi-steady formation assumption, and how best this theory might be modified to have wider application.

The distinguishing features of a break-up jam are illustrated in Figure 3.2. Evident is the downstream ice cover that resisted break-up, the fractured ice sheet that forms the transition between the solid-ice and the quite sudden change to the very fragmented ice that forms the body of the jam. An important question is what the ice cover transition from solid ice sheet to open water looks like in profile, as the maximum water level produced by the jam depends strongly on this ice cover profile. In the current absence of an ability to measure accumulation thickness directly, field measurement and analysis of water levels through the jam, and physical model studies using correctly scaled model ice, could provide information on this.

A related question is the ratio of the volume of ice in the jam to the original volume of ice in the contributing reach upstream of the jam. In some circumstances this ratio can provide an important constraint on the maximum size of an ice jam, and thereby on the

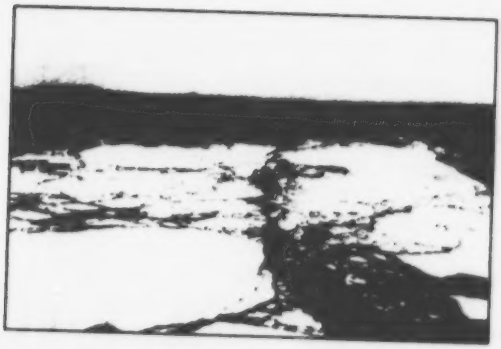

Figure 3.2. Looking upstream over an ice jam on the Mackenzie River near Fort Norman, N.W.T.

maximum water level.

One important aspect of jam development that has had little investigation is the erosion and deposition of both ice and bed material under an ice jam. There is field evidence that bed scour under an ice jam can be considerable, and can have important implications with regard to pipeline and bridge pier design. In addition, erosion of ice fragments from beneath the jam as it thickens may be an important limiting process in jam development, for both freeze-up and break-up jams.

Another common limitation to jam development is flow diversion around the jam. After the water level reaches the flood plain, water (and perhaps ice) can move around the jam. This is a common occurrence in the field. Laboratory and analytical studies should be able to give some indication of how the ice jam responds once the accumulation begins to be lifted above the restraint of the banks and the proportion of the flow moving under the jam decreases. Similar circumstances prevail in deltas when the backwater from a jam allows flow to move down secondary channels.

In the more settled regions of the country it is not uncommon for ice jam accumulations to become entangled with bridge superstructures. Although on large rivers this may be catastrophic for the

structures, on small streams the structure will likely remain in place and contribute support to the ice jam. No procedure has been evaluated for determining the magnitude of this support. A related, and probably more common question is the magnitude of the loads an ice jam can exert on bridge piers and superstructures. While these are likely not nearly as large as commonly imagined, some simple laboratory tests should help resolve the matter.

3.3.3. Jam Failure

Like ice jam formation, another feature about which very little is known is what causes an ice jam to fail. One mode is a slow melt brought about by warm weather and the increasing temperature of water moving down the river. However, what are far more perplexing and important are the conditions that will give rise to sudden failure of an ice jam. Useful contributions to understanding this problem could be provided by appropriate laboratory studies using model ice. A particular item of interest is how an ice jam responds to a surge moving down from upstream, such as would be caused by sudden heavy rain in the catchment, or sudden failure of a jam upstream. Presumably the response will depend in large measure on the nature of the "key" of the ice jam.

Sudden failure of the ice jam is usually the objective of emergency measures initiated after ice jam flooding begins. One common method is to use explosives to try to accomplish this but, as many case studies attest, it is not often successful. Another technique used to break up ice jams in navigation channels is "surging", using sudden releases from upstream storages. An important need is an investigation of such ice jam removal techniques with two aims: to determine the best approach in various circumstances and, perhaps more importantly, to better define the limits of what can be achieved and hence avoid the risk of life and property that often attends attempts at ice jam removal.

An understanding of ice jam failure is probably the most important and pressing problem with regard to ice jams. Almost no fundamental research has been done on the subject.

3.4. INSTRUMENTATION

Strong limitations on field research on ice jams are imposed by limited field techniques. Possibly the major problem is the current inability to directly measure ice accumulation thickness and strength. Although good indications of thickness can be obtained indirectly, such as from the thickness of shear walls left behind after ice jam failure, or from analytical simulation of measured water level profiles, direct measurement of accumulation thickness throughout an ice jam would remove many doubts and allow a major advance in the understanding of ice jams. It is commonly felt that, at least in large rivers, radar techniques may allow determination of jam thickness despite the necessary poor definition of the lower accumulation boundary. Therefore, an important need is a thorough evaluation of the limitations of radar measurement of ice jam thickness.

Accumulation strength is another important ice jam parameter that to date has only been inferred. It would be most useful to measure this strength directly. One technique that has been suggested (D.D. Andres, Alberta Research Council, personal communication) is the use of pairs of piles or plates inserted into the accumulation from a bridge and then jacked apart. Obviously such an experiment would require substantial field support but it does seem feasible, particularly for freeze-up accumulations and measurements of the strengthening provided by the formation of a solid ice layer within the accumulation.

A fundamental need in any analysis of ice jam behaviour is knowledge of stage and discharge, and their variation in periods as short as an hour or so. The unreliability of standard discharge measurement techniques during freeze-up and break-up is legend. Even reasonably reliable measurements of stage during such events seems to be beyond the capacity of the standard techniques used by the hydrometric measurement establishment. Because of this, available discharge estimates during break-up and freeze-up are based on extrapolation from other stations often far removed from the site of interest, so that even estimates of the mean daily discharge are frequently in error by a factor of two or more. The most fundamental

need is therefore the development of a more reliable, but still relatively inexpensive, method of stage measurement, particularly for large rivers. A change in emphasis to measuring stage from above, rather than from below, may help in this. For example, remote recording of stage using time-lapse (infrared?) photographs may be a reasonable alternative to the simple and effective, but manpower expensive, periodic surveillance by observers. Doubtless other techniques will be devised and applied once the importance of the problem, and the fact that the technique only has to be used for a limited period of time, is recognized.

Limitations imposed by the continually varying stage-discharge relationship during such events is generally much less than commonly perceived, and in no way negates the value of reliable stage measurement. Nevertheless, direct measurement of discharge during such events would be even more valuable. If a method of doing this could be developed, even if only applicable on small streams, would be a very worthwhile contribution. However, the only relatively inexpensive techniques that come to mind and that may have some value are tracer methods. Other, much more expensive possibilities might include ultrasonic or electromagnetic techniques.

3.5. MODELS

3.5.1. Physical Models

The use of scaled physical models has been suggested several times in the above. A review of scale-model relations and the state-of-the-art in model ice production suggests that such models are viable. Without doubt, because of the ease of handling it, the most convenient scale-model ice is ice itself, doped as necessary to get the need reduction in strength, although its use does require a refrigerated laboratory. Considerable pioneering work on the use of such model ice has been carried out at the U.S.A. CRREL laboratories (D.J. Calkins, personal communication). However much remains to be learned, and the need for refrigerated facilities is a strong limitation. In lieu of this the possibility remains of developing satisfactory, non-proprietary, artificial model ice and investigating its use in model studies at room temperature.

3.5.2. Analytical Models

Availability of analytical solution techniques do not currently impose a limitation on the simulation of ice jam behaviour. Rather the limitation lies in the poor understanding of the ice jam processes, particularly ice jam formation and failure. Nevertheless computer simulation of ice jam formation and development, and the effect on discharge and stage, would help highlight the important weaknesses in the present understanding and, at least indirectly, by application and trial and error, assist in improving that understanding. Serious gaps will likely become apparent when trying to fit all the pieces together, but this in itself will make the exercise worthwhile. The fact that these gaps will, at present, have to be fitted with speculative, undocumented assumptions to complete the package will not be debilitating, as long as these, and the limitations they impose, are clearly identified. Such models would at least serve as a convenient summary and test of the state-of-the-art and, in this computer-oriented society, provide an effective means for technology transfer. Strangely, there is at present no non-proprietory computer model of ice jam formation and development, for either freeze-up or break-up. With regard to return for investment, the development, publication and servicing of such models would seem to be an important need in ice jam research. Every effort should be made to encourage an appropriate Government research agency to undertake such development, as only a Government agency can ensure the necessary non-proprietary status of the model and provide the required long-term servicing of it.

Another worthwhile research topic would be an empirical study of the hydrometeorological conditions necessary for major ice jam formation. Such a study would be based on an analysis of historical data on ice jam formation at selected sites, and involve relating ice jam occurrence to pertinent meteorological data available for the same period. A few studies of this type have been published and have generally been successful in discerning at least approximate cause and effect relations. A thorough review of such studies would be a worthwhile study in itself.

3.6. SUMMARY AND CONCLUSIONS

Ice jams are a subject of increasing concern. Canada has a large vested interest in the subject and should obviously play a leading role in the necessary research. Despite the progress over the last two decades, development of a real understanding of ice jam fundamentals has only just begun. From the multitude of possible ice jam research topics, only some of which have been mentioned above, probably the most important, in terms of plausibility and return for investment, would be:

* Systematic field observation and measurement of ice jam behaviour. It is important that these be combined with observations of freeze-up or break-up, as appropriate, over a long reach of the river.

* Development of non-proprietary computer models of ice jam formation and development at freeze-up and break-up, and their effect on discharge and stage, incorporating the present understanding of ice jam processes.

* Investigation, in the field, laboratory and office, of lodgement at freeze-up.

* Development of non-proprietory artificial model ice, and analytical and experimental assessment of scaling requirements for physical models of ice jams and break-up.

* Development and use of better methods of remote measurement of stage during freeze-up and break-up periods.

* Further laboratory and analytical investigations of the fundamentals of ice fragment and accumulation behaviour under steady and unsteady flow conditions.

* Laboratory investigations of the formation of ice jams under unsteady flow conditions. Modelling the mechanical properties of the solid ice cover will be an important component.

* Analytical and laboratory simulation of surge generation, propagation and decay in the presence of solid and fragmented (ice jams) ice covers.

3.7. ACKNOWLEDGEMENTS

This paper is presented as a synthesis of the various research needs suggested by the members of the Working Group on River Ice Jams of the Subcommittee on Hydraulics of Ice-Covered Rivers. The support provided by U.S.A. CRREL in the preparation of this manuscript is gratefully acknovledged.

3.8. REFERENCES

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Chapter 4. CASE STUDIES CONCERNED WITH ICE JAMMING

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4.1. INTRODUCTION

On many rivers experiencing ice jams, studies have been carried out by various entities concerned with planning, design, construction and operation of river development projects. Unfortunately, many important case studies concerned with ice jams have not been published in well known publications.

The NRCC Working Group on River Ice Jams was established in 1982 to help improve the available technology for dealing with ice jams. Task Number 4 of the Working Group is concerned with documentation and publication of case studies concerned with ice jams. In order to help carry out this task, about 35 persons were contacted from different organisations in an effort to identify as many case studies as possible, particularly for cases which have not been published in well known publications. As a result, 81 short case study descriptions have been received and are presented in the "Casebook on Ice Jams" (Petryk, 1985). The Casebook presents these short descriptions, each of which gives an outline of the ice jam related work carried out, in progress, or planned. In addition, the short description identifies reference documents and contact person(s) associated with each case study. Appendix 4.A gives six examples of case studies taken from the Casebook.

The casebook is designed to be an ice jam source catalogue from which interested users can determine relevant studies, reports and contacts from which more detailed information can be obtained. It should increase the exchange of ice jam field data and results of studies among ice specialists and engineers. This exchange of information is vital to improving our state-of-the-art of dealing with ice jams.

4.2. PRESENTATION OF THE CASE STUDIES

Table 4.1 gives a summary of the case study descriptions; each case study is described with the following information:

- Case number assigned for reference purposes.
- Title of case study and location of river.
- Field conditions studied and/or observed.
- Person to contact if more information is desired.

The Appendix 4.B of this report gives a bibliography of case studies available in well known publications.

4.3. ICE JAM TOPICS TREATED BY CASE STUDIES

A wide range of ice jam topics are covered amongst the case study descriptions given in Appendix 4.A and summarized in Table 4.1. The following subjects are treated, amongst others:

- Thermal heat balance in a river during freeze-up and spring break-up.
- Freeze-up, ice jamming, ice cover progression and shoving.
- Spring break-up and ice jamming.
- Winter break-up and ice jamming.
- Ice thickness measurements.
- Design criteria for ice regime calculations (natural and regulated river flow conditions).
- Documentation and studies of past ice jam flooding events.
- Ice jam frequency and magnitude from botanical evidence.
- Ice jam effects on river bank and bed erosion.
- Analysis and observation of hydraulic transients created by a relatively sudden ice jam release.
- Analysis, control and observations of ice regime upstream and downstream of existing hydro-electric works.
- Ice studies and field surveys for future hydro-electric works.
- Effects of hanging dams on break-up and ice jamming.
- Numerical models of river ice regime (developments, calibrations, and applications).
- Physical modelling of a river ice regime.

- Prevention and control of ice jams by means of weirs, islands, ice booms, excavations, flow and level regulation, cutting slots in solid ice cover, ice removal, blasting, and storage of ice in flood plains.
- Wind and lake seiche effects on ice jamming.
- Hydrometeorological effects on break-up and ice jamming.
- Documentation of damages due to flooding caused by ice jams.
- Flood-plain mapping studies including ice jam effects.
- Engineering studies concerned with ice jam control measures and structures for hydro-power and flood control projects.
- Surveys of ice blockages in powerhouse approach canals.
- Aerial and ground surveys of ice jams (locations, profiles, and affected reaches).
- Ice jamming near river tributary junctions.

Herein, only a few examples of the available case studies are presented (Appendix 4.A). For copies of any particular case study listed in Table 4.1, contact Dr. Terry Prowse.

4.4. FUTURE PUBLICATIONS OF CASE STUDIES CONCERNED WITH ICE JAMS

4.4.1. Types of Publications

In the future, the NRCC Working Group on River Ice Jams will be encouraging and facilitating the publication of additional case studies according to the following four formats:

a) Additional short descriptions of case studies to be added to this casebook. Periodically this casebook will be updated with the new contributions from researchers and practitioners working in the ice jam field of interest. The recommended format for these short descriptions of case studies is described below in section 3.2.

b) Technical articles presented in semi-formal format to be presented at technical meetings. Publication in the proceedings of the NRCC Workshops on the Hydraulics of River Ice will be particularly encouraged.

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers in Yukon and Northwest Territories		
T101	Ice Regime of the Lower Mackenzie River and Mackenzie Delta (N.W.T.)	Freeze-up, pre-break-up ice thicknesses, and break-up	1) J.C. Anderson Environment Canada Ottawa
T102	Liard and Mackenzie River Ice Break-up Fort Simpson (N.W.T.)	Break-up and ice jams	T.D. Prowse or J.C. Anderson Nat. Hydrology Research Centre (NHRC), Saskatchewan
T103	Historical Flood Review, Mackenzie River Basin	Flooding due to ice jams during spring break-up	J.C. Anderson or T.D. Prowse Environment Canada - Ottawa
T104	Ice Jams and Break-up on the Yukon River, Dawson City (Yukon)	Break-up and ice jam floodings	1) S.C. Sigras, NHRI, Ottawa 2) J. McLachlan Indian and Northern Affairs Canada Whitehorse (N.W.T.) 3) R.O. Lyons Inland Waters Directorate (IWD) Vancouver (B.C.)
T105	Flood Risk Mapping, Hay River (N.W.T.)	Break-up and ice jams, design criteria for ice regime	Dept. of Indian and Northern Affairs - Yellowknife (N.W.T.)
T106	Spring Break-up Observations at Pipeline River Crossings in the Keewatin District, Tholon and Kazan Rivers (N.W.T.)	Effects of break-up on river bank erosion	J.C. Anderson Environment Canada - Ottawa
T107	Mackenzie River Near Arctic Red River (N.W.T.)	Observation of ice jam release	C.R. Neil or R.H. Cooper Northwest Hydraulic Consultants Edmonton
T108	Mackenzie River at Fort Simpson	Ice jam observations including water level measurements	1) F.E. Parkinson LaSalle Hydraulic Laboratory LaSalle (Quebec) 2) L.J. Parmley, B.C. Hydro Vancouver (B.C.)
T109	Mackenzie River at Norman Wells	Breakup and ice jamming	Same as for Case T108
T110	Mackenzie River at entrance to Mackenzie Delta	Massive ice jams	Same as for Case T108
T111	Liard River at Beaver Dam	Freeze-up ice jamming	Same as for Case T108

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers in Western Canada		
T112	Liard River at Fort Liard	Freeze-up ice jamming	Same as for Case T108
T201	Freeze-up Jamming and Effectiveness of Ice Anchor on the Reduction of Flood Levels on the Bow River (Alberta)	Freeze-up ice jamming	1) D. Andres Alberta Research Council Edmonton 2) G. Fenstad Alberta Environment, Edmonton
T202	Spring Melt and Break-up in a Central Alberta Basin	Ice jamming at freeze-up	Same as for Case T201
T203	Freeze-up on the North Saskatchewan River at Edmonton (Alberta)	Observation and analysis of freeze-up	1) D. Andres Alberta Research Council, Edmonton 2) B. Gerard University of Alberta, Edmonton
T204	Freeze-up Jams and Associated Water Levels on the North Saskatchewan River at Rocky Mountain House (Alberta)	Observation and analysis of freeze-up downstream of power dam	1) P. Doyle Trans Alta Utilities Corp., Calgary 2) D. Andres Alberta Research Council, Edmonton
T205	Ice Related Problems on the Peace River at the Town of Peace River (Alberta)	Freeze-up, break-up, and ice jamming	Same as for Case T201
T206	Break-up and Ice Jams on the Athabasca River at Fort McMurray (Alberta)	Profiles of ice jams, and surges resulting from ice jam failure	1) D. Andres Alberta Research Council, Edmonton 2) H. Richert Alberta Environment, Edmonton
T207	The Ice Regime of the Peace River in the Vicinity of Portage Mountain Development, Prior to and during Diversion (B.C.)	Formation and break-up of hanging dams and ice jams	F. Sampson B.C. Hydro - Vancouver
T208	Observation and Analysis of Freeze-up Jams on the Peace River near Taylor (B.C.)	Observation and numerical modeling of freeze-up ice jam	C.V. Kartha or V. Keenhan B.C. Hydro - Vancouver
T209	Peace River at Town of Peace River (Alberta)	Ice Jam water levels associated with fluctuating hydro plant releases	1) C.R. Hall Northwest Hydraulic Consultants 2) D.D. Andres Alberta Research Council, Edmonton

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers in Western Canada (continued)		
T210	Nelson River at Long Spuce Project	Ice jam development accompanied by massive shove	1) F.E. Parkinson LaSalle Hydraulic Lab., Montréal 2) P.D. Wang Manitoba Hydro, Winnipeg 3) R. Carson, Crippen-Acres Winnipeg (Manitoba)
T211	Hydrometric and Climatic Data Analysis of Ice Break-up Events in the Red Deer River	Break-up	D. Smith University of Calgary
T212	Determining Frequency and Magnitude of River Ice Jams and Drives from Botanical Evidence	Ice jam frequency and magnitude from botanical evidence	D. Smith University of Calgary
	Rivers in Central Canada		
T301	Rivière des Milles Îles - Étude du régime des glaces (Quebec)	Analysis of ice regime and identification of methods to eliminate flooding	A. Carpentier J. Monfet R. Poulin Ministère de l'Environnement Sainte-Foy (Quebec)
T302	Étude du régime des glaces pour solutionner des problèmes d'inondation à Richmond (Quebec)	Ice observations to calibrate mathematical model and examination of measures to reduce flooding	G. Barbé Ministère de l'Environnement Sainte-Foy (Quebec)
T303	Construction d'une estacade sur la rivière Saint-Charles (Quebec)	Ice Boom and weir constructed to control ice regime	A.-R. Tremblay and A. Valcourt Ministère de l'Environnement Sainte-Foy (Québec)
T304	Mathematical model RIVICE (Quebec)	Mathematical model of river ice and thermal regime applied to Quebec rivers	H. Marcotte T. Quach Hydro-Québec - Montréal J.-P. Saucet LaSalle Hydraulic Laboratory Montréal (Quebec)
T305	Richelieu River between Chambly and Lake Champlain	Observations and simulation of river ice regime	Same as for Case T304

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers in Central Canada (continued)		
T306	Chaudière River at Charny (Quebec)	Ice blockage of approach canal to power house	M. Marcotte Hydro-Québec - Montréal
T307	Unpublished, Ice Jam Events of 1979, 1981, 1982 and 1984, Thames River (Ontario)	Observation, analysis of field data, and computation of ice jam profiles	W.L. Knowles MacLaren Engineers Inc. London (Ontario)
T308	St. Lawrence, International Rapids Section (Ontario)	Prevention of important ice jams by excavations, ice booms and flow control	D.M. Foulds Uxbridge (Ontario)
T308A	Water Management Study of the Raisin River, Cornwall (Ontario)	Observation and analysis of ice conditions from freeze-up to break-up over several years	D. Hodgins MacLaren - Plansearch Toronto
T309	Niagara River, Lake Erie to Lake Ontario	Control of ice jamming by flow control, excavations, and ice booms. Effects of lake seiche on ice regime.	Same as for Case T308
T308	Nadeweska (Ontario)	Effects of hydro releases on ice regime	Same as for Case T308
T311	Mississeqi River (northern Ontario)	Effects of hydro releases on downstream flooding with ice effects	Same as for Case T308
T312	Kawinistikwa River, north western Ontario, Thunder Bay	Hydrometeorological effects on ice jamming	Same as for Case T308
T313	Town Creek in Timmins (Ontario)	Aufeis flooding	Same as for Case T308
T314	Aubrey Falls Generating Station Winter Peaking Restrictions (Ontario)	Effects of powerhouse operation on ice jams resulting from broken ice and frazil	T.E. Wigle Ontario Hydro - Toronto
T315	Ice Cover Collapse on the St. Lawrence River	River ice observations and ice cover thickness measurement. Control of ice regime with powerhouse operation.	Same as for Case T314

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers in Central Canada (continued)		
T316	Port Bruce Preliminary Engineering Study (Ontario)	Assessment of flood damages with and without ice jams. Feasability of flood control measures.	H. Belore Cumming-Cockburn & Assoc. Willowdale (Ontario)
T317	Brisco Dam Ice Control Capability (Ontario)	Assessment of ice jam flooding problem with the help of a mathematical model	Same as for Case T316
T318	Lower Credit River Ice Control Study (Ontario)	Assessment of ice jamming and identification of remedial measures	Same as for Case T316
T319	Lonsdale Dam (Ontario)	Identification and analysis of ice jam problems with the help of a mathematical model	Same as for Case T316
T320	Lott Dam/College Street Dam (Ontario)	Effects of six dams on the ice regime of the Moira River	John Jutta Cumming-Cockburn & Assoc. Willowdale (Ontario)
T321	Criteria for Stability of Ice Covers in Rivers St. Lawrence River (Ontario)	Observations and analysis of ice jamming. Comparison of theory with observations	D. Witherspoon Great Lakes St. Lawrence Study Office Cornwall (Ontario)
T322	Ice Management on the Rideau River, Ottawa	Ice Jam control measures	D.G. Curry City of Ottawa Ottawa (Ontario)
T323	Field Studies of River Ice Jams and Flooding Thames River and Grand River (Ontario)	Documentation and analysis of freeze-up, break-up and ice jamming	S. Beltaos National Water Research Institute Burlington (Ontario)
T324	Ice Considerations in the Design of Lac Robertson Hydro-Electric Plan (Quebec)	Analysis of solid ice cover break-up, ice jamming and melting effects	S. Petryk Tecsult Inc. Montréal
T325	Ice Considerations at LG2-PA Powerhouse Expansion (Quebec)	Evaluation of ice regime in power plant intake canal	Same as for Case T324
T326	St. Lawrence River Ice Studies for Harnessing the Lachine Rapids in Montréal	Frazil and ice jamming effects on the design and operation of hydro-electric works	R.J. Silver Consultant Montréal

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers in Central Canada (continued)		
T327	Observations of Ice Conditions on the St. Lawrence River (Ontario and Quebec)	Documentation of ice regime by various entities	1) Ontario Hydro 2) Hydro-Québec 3) Saint Lawrence Seaway Authority 4) International Power Commission
T328	Ice Management - Moira River	Assessment of ice-related flooding, and design of capital works to control it	1) J. Kelleher Moira River Conservation Authority Belleville (Ontario) 2) M. Beasley Kilborn Engineering Ltd. Toronto
T329	Chateauguay River, at mouth, Lake St. Louis	Proposed ice jam study site	F. Parkinson LaSalle Hydraulic Laboratory Montréal
T330	Credit River Ice Study in Town of Halton	Effects of ice control works on break-up	D.J.S. Tefft Credit Valley Conservation Authority Meadowvale (Ontario)
T331	Lower Credit River Ice Control Survey, 1984	Techniques for monitoring break-up and formation of ice jams	Same as for Case T330
T332	Lower Credit River Ice Control Study	Ice cover formation and break-up characteristics	Same as for Case T330
T333	Erindale Park Ice Storage Investigation	Ice storage locations investigation	Same as for Case T330
	Rivers Located in Atlantic Canada		
T401	Environmental Assessment of Dickey-Lincoln Project (N.B.)	Cyclical ice formation, break-up and jamming downstream of power dam	U.S. Army Corps of Engineers New England Division Waltham (Massachusetts)
T402	Walker Brook Hydrotechnical Study Canada (N.B.) Flood Damage Reduction Program	Effects of debris and ice jams on water levels	H. Belore Cumming-Cockburn & Assoc. Willowdale (Ontario)

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers Located in Atlantic Canada (continued)		
T403	Hydrotechnical Study of Stephanville Area Canada, Newfoundland Flood Damage Reduction Program	Comparison of flood levels with and without ice and debris jams. Simulations with HEC - Ice and MMRI empirical procedures	Same as for Case T402
T404	On-going Field Observation Program (N.B.)	Ice cover thickness, qualitative ice regime descriptions, ice jam locations, etc.	B.C. Burrell Environment New Brunswick Fredericton (N.B.)
T405	Hydrotechnical Study-Black Duck/Stephenville Crossing, Harrey's River, (Newfoundland)	Documentation, field surveys, and analyses of open water, freeze-up and break-up conditions	J.E. Anderson Acres International Limited Niagara Falls (Ontario)
T406	Saint John River Analysis of 1976 Ice Jams	Analysis of severe 1976 ice jams. Effects of river operations water levels and ice jams.	S. Ismail N.B. Power Fredericton (N.B.)
T407	Flood Remedial Action Study, Mill Brook, Kentville (N.S.)	Observation and analysis of ice conditions from freeze-up to break-up	D. Hodgins MacLaren Plansearch Toronto
T408	Hydrotechnical Study of the Badger and Rushy Pond Area, Exploits River (Newfoundland)	Extensive measurements of type, thickness, elevation, and evolution of ice covers from freeze-up	Same as for Case T407
T409	Hydrotechnical Study of the Antigonish Area Flood plain, Rights River, Bryerly Brook (N.S.)	Observations and measurements of ice evolution from freeze-up to break-up for several years, including ice-jam measurements	Same as for Case T407
	Rivers Located in More than One Region of Canada		
T501	Liard - Mackenzie Winter Regime Study (B.C. and N.W.T.)	Effects of hydro power operation on ice regime. Ice regime observations. Development and application of mathematical model.	L.J. Farmley B.C. Hydro Vancouver

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers Located in More than One Region of Canada (continued)		
T502	River Ice Break-up, Fort Nelson (B.C.) and Lower Liard River (N.W.T.)	Ice thickness, break-up, location and severity of ice jams.	T.D. Prowse or J.C. Anderson NHRC - Saskatoon
T503	Annotated Bibliography on River Ice Regimes	Freeze-up, ice jams, break-up, river regulation effects on ice regime, etc.	J.C. Anderson Environment Canada Ottawa
T504	Experience with the Numerical River Ice Model "SIMULACE"	Development and applications of numerical river ice model.	S. Petryk Tecsult Inc. Montréal
T505	Development of a Comprehensive Numerical River Ice Model	Numerical simulation of different ice conditions on a number of rivers.	Same as for Case T504
T506	List of Ice Studies Done by the LaSalle Hydraulic Laboratory	Field observations and bathemetric surveys, physical and numerical modeling, freeze-up, frazil and anchor ice, floating sheet ice, ice cover evolution, break-up, water temperatures, etc.	F. Perkinson LaSalle Hyd. Lab. LaSalle (Quebec)
	Rivers Located Outside of Canada		
T601	Observation of River Ice Break-up on Alaska Rivers	Aerial photos of ice break-up, ice and water measurements to develop mathematical model of break-up	T.E. Osterkamp J.P. Gosink University of Alaska Fairbanks (Alaska)
T602	Gunison River Ice Jams	Variables affecting ice jamming	P. Burgi Bureau of Reclamation Denver (Colorado)
T603	Emergency Ice Jam Analysis Winnoski River (Vermont)	Control of water levels by mechanically removing an ice jam	D.J. Calkins U.S. Army, Cold Regions Research and Engineering Laboratory (USACRREL) Hanover (N.H.)

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

Case Number	Title of Case Study and Location of River	Field Conditions Studied and/or Observed	Contact
	Rivers Located Outside of Canada (continued)		
T604	Ice Jams on Missisquoi River at Richford (Vermont)	Effects of a 12-ft high dam removal on freeze-up and ice jam conditions	Same as for Case T603
T605	Ice Jams on the Lamoille River in Hardwick (Vermont)	Several freeze-up and break-up ice control measures to control flooding in town	Same as for Case T603
T606	Ottauquechee River Ice Studies (Vermont)	Observations from freeze-up through break-up; numerical and physical modelling	Same as for Case T603
T607	Ice/Hydraulic Measurements - Salmon River (Idaho)	Frequency analysis of ice jamming, benefit-cost studies of alternative remedial measures	Same as for Case T603
T608	Isreal River Ice Jam Remedial Measures	Ice control measures on a tributary river	Same as for Case T603
T609	Ice Jams on the Susquehanna near Binghamton (NY)	Ice jam flood frequency analysis; study of alternative ice control measures	1) S. Apfelbaum Baltimore District, Corps of Engineers Baltimore (Maryland) 2) D.J. Calkins (USACRREL) Hanover (N.H.)
T610	Ice Control on Casenovia Creek, Buffalo (NY)	Ice control measures upstream and downstream of a steep shallow stream reach; physical modelling	D.S. Deck (USACRREL) Hanover (N.H.)
T611	Oil City Ice Control Structures (Pennsylvania)	Control of ice jam by means of an ice boom and over-flow weir	D.S. Deck (USACRREL) Hanover (N.H.)

TABLE 4.1. LIST OF CASE STUDIES CONCERNED WITH ICE JAMMING (continued)

c) Publication through the NRCC Working Group of formal and informal reports on case studies giving a detailed description of field data collected and/or a complete description of the results from a study on a given river.

d) Publications of formal technical articles in well known hydraulics and river ice publications such as the Canadian Journal of Civil Engineering, ASCE Journal of Hydraulic Engineering, International Symposium on Ice, etc.

4.4.2. Recommended Format for Future Contributions to the "Casebook"

The Working Group is seeking new descriptions of case studies for future editions of the casebook. As illustrated in Table 4.1, the short descriptions are classified according to the regional location of each river. These regions are: Yukon and Northwest Territories, Atlantic Canada, Central Canada, Western Canada, "Rivers located in more than one region of Canada", or "Rivers Outside of Canada". Therefore, each case study should be presented individually, normally varying in length from one to about ten pages. The following format is preferred, although alternate formats will be considered for publication:

1) Title
2) Name and location of river
3) Scope of work
4) Status of work
5) References (if any)
6) Contact(s)
7) Date of submission, and person contributing the case study description (if different from the contact person).

The short case study descriptions should be submitted to:

T.D. Prowse
National Hydrology Research Institute
11 Inovation Boulevard
Saskatoon (Saskatchevan)
S7N 3H5

4.5. CONCLUDING COMMENTS

Most parts of Canada experience an important degree of ice jamming on their rivers. Because of the complexity and limited knowledge of ice jams, reporting of field observations and ice jam related studies on particular rivers is very important to both researchers and engineers. For this reason the Working Group on River Ice Jams, by means of this report and the "Casebook on Ice Jams" (Petryk, 1985) has published a list of case studies and contact persons to promote the exchange of ice jam related information.

In the future the Working Group plans to continue encouraging publication of case studies according to the methodology outlined in section 4.0.

4.6. ACKNOWLEDGEMENTS

This report and the "Casebook on Ice Jams" has only been possible by the contributions of the persons and agencies which are listed in Table 4.1. The NRCC Working Group on River Ice Jams is grateful to each of these contributors. The resulting exchange of information between engineers and researchers should help advance the state of the art in the difficult field of ice jams.

APPENDIX 4.A. EXAMPLES OF CASE STUDY DESCRIPTIONS TAKEN FROM THE "CASEBOOK ON ICE JAMS" (Petryk, 1985)

TITLE: **LIARD AND MACKENZIE RIVER ICE BREAK-UP**

LOCATION: Fort Simpson region, N.W.T.

SCOPE OF WORK: Results on the 1982 and 1983 field monitoring program have been published -- increased emphasis has been placed on the measurement of ice jam characteristics -- work in spring of 1983 and 1984 included water and ice surveys, micro-meteorological studies of the river ice energy balance prior to break-up, water temperature measurements prior to and following break-up, testing of a false parallax method of photography for measuring river velocities while running ice is present and measurement of temperature and velocity profiles within jams.

RELEVANT PUBLICATIONS:

Prowse, T.D., 1984. Liard and Mackenzie River ice breakup, Fort Simpson region, N.W.T. 1983. Internal report, prepared by National Hydrology Research Institute, Environment Canada, for the Water Resources Division, Department of Indian Affairs and Northern Development, Ottawa, Ontario, February, 84 pp.

Anderson, J.C., 1982. Liard and Mackenzie River ice breakup, Fort Simpson Region, N.W.T. 1982. Internal report, prepared by National Hydrology Research Institute, Environment Canada, for the Water Resources Division, Department of Indian Affairs and Northern Development, Ottawa, Ontario, September, 37 pp.

- publications by the National Hydrology Research Institute relevant to "false parallax" method:

MacKay, D.K., D.A. Sherstone and K.C. Arnold, 1974. Channel ice effects and surface water velocities from aerial photography of Mackenzie River breakup. Further Hydrologic Studies in the Mackenzie Valley, Environmental Social Committee, Northern Pipelines, Report No.74-35, Ottawa, July 1974, 71-108

Sherstone, D.A., 1973. Remote sensing technique applied to current velocity measurements and river ice jamming. Fluvial Processes and Sedimentation, May 1973, Edmonton, Alberta, 403-419

CONTACTS: Dr. T.D. Prowse
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SUBMISSION: Dr. T.D. Prowse
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TITLE: **ICE-RELATED PROBLEMS ON THE PEACE RIVER AT THE TOWN OF PEACE RIVER, ALBERTA.**

LOCATION: Peace River at Peace River, Alberta.

SCOPE OF WORK: High water levels associated with break-up on the Peace River and the Smoky River, and more recently, during freeze-up on the Peace River, have resulted in near flood situations, and has resulted in high ground-water levels causing seepage flooding into basements in some subdivisions in the Town of Peace River. Since 1974, break-up has been observed almost annually (missing 1976/77, 1977/78, 1979/80 and 1980/81), and interest in freeze-up has increased since the 1981/82 high freeze-up levels. The Peace River has been regulated since 1968 by the W.A.C. Bennett Dam in B.C., where flows have been re-regulated by the Peace Canyon Dam since 1980. Good discharge records and adequate meteorological data, coupled with well defined channel geometry and two functioning gauges within a short reach, have resulted in excellent records since 1976. Since 1981/82, the data collection effort has been expanded to include records of ground-water levels at three locations in one of the seepage prone subdivisions, as well as freeze-up advance and break-up recession rates in the river. Break-up, when it occurs in the thermal mode, has also been well documented and analysed. However, when large jams form, only ice jam profiles have been documented, and all of the classical difficulties and short-comings are evident.

STATUS OF WORK: Numerous reports have been written, documenting both freeze-up and break-up. Since the 1981/82 freeze-up event, which caused record high river levels at Peace River, efforts have been concentrated on data collection. At present, efforts are being made to fill in gaps in previous documentation, and limited analyses are about to begin.

REFERENCES:

Acres Consulting Services Ltd., 1980. Dunvegan Power project, Peace River ice study. Report prepared for the Energy Resources Conservation Board, Edmonton, Alberta

Acres Consulting Services Ltd., 1980. Behaviour of ice covers subjected to large daily flow and level fluctuations. Peace River Ice Regime Study, Vol.III, Report prepared for the Canadian Electrical Association, Montréal, Quebec

Andres, D.D., 1975. Ice breakup observations and mitigation at the town of Peace River, April 1975. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 103 pp.

Andres, D.D., 1978. Effects of the Dunvegan Dam on the ice regime of the Peace River at the town of Peace River. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 57 pp.

Carson, R.K. and S.T. Lavender, 1980. A discharge/water level relationship for ice cover stability. Proceedings of the Workshop on the Hydraulic Resistance of River Ice, G. Tsang and S. Beltaos (Editors), 23-24 September 1980, National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario, 112-115

Davies, L.B., R.K. Deeprose and H.M. Hunt, 1981. Observations and report on river ice conditions in the Peace River basin 1978-1979. Report by the Alberta B.C. Joint Task Force to the Alberta and B.C. Ministries of the Environment, 40 pp.

Davies, B., R.K. Deeprose and H.M. Hunt, 1984. Observations and report on river ice conditions in the Peace River basin 1981-1982. Report by the Alberta B.C. Joint Task Force to the Alberta and B.C. Ministries of the Environment, 106 pp.

Davies, L.B., J. Parmley, R.K. Deeprose and H.M. Hunt, 1984. Observations and report on river ice conditions in the Peace River basin 1982-1983. Report by the Alberta B.C. Joint Task Force to the Alberta and B.C. Ministries of the Environment, 8 pp.

Fonstad, G.D., 1982. Peace River 1981/82 ice observation report. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 61 pp.

Fonstad, G.D., 1986. Peace River ice observation report 1984/85. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 75 pp.

Fonstad, G.D. and L.A. Garner, 1984. Summary report, Peace River ice observations 1982/83 ice season. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 22 pp.

Fonstad, G.D. and L.A. Garner, 1986. Peace River ice observation report 1983/1984. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 76 pp.

Garner, L.A., 1979. Ice breakup observations at the town of Peace River, 1979. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 20 pp.

H. Biberhofer Consulting, 1984. Peace River ice study. Consultant's Report prepared for the River Engineering Branch, Technical Services Division, Alberta Environment, Edmonton, Alberta, 50 pp.

Northwest Hydraulic Consultants Ltd., 1982. Evaluation of 1982 river ice conditions at Peace River. Consultant's Report to the River Engineering Branch, Technical Services Division, Alberta Environment, Edmonton, Alberta, 36 pp.

Nuttall, J.B., 1974. Report on ice breakup at Peace River, Alberta, 1974. Consultant's Report to the River Engineering Branch, Technical Services Division, Alberta Environment, Edmonton, Alberta, 54 pp.

Szabon, W., 1977. Ice breakup observations and mitigation at town of Peace River, April, 1976. River Engineering Branch Report, Technical Services Division, Alberta Environment, Edmonton, Alberta, 77 pp.

CONTACTS:

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TITLE:	**CONSTRUCTION OF AN ICE BOOM ON THE ST. CHARLES RIVER**[1]
SCOPE:	The Ministère de l'Environnement du Québec, acting on behalf of Québec built this structure in the summer 1983.
OBJECTIVE OF THE STRUCTURE:	Protection of flooding due to the ice of a highly urbanised area of Québec.
DESCRIPTION OF THE STRUCTURE:	A weir, creating a pond about 600 m long and 60 m wide was constructed with a rigid ice boom structure. The weir enables the creation of a deep pond with a depth of about 2.5 m near the weir. The rigid ice boom is composed of abutments and four piers spaced at 4.1 m intervals.
MODE OF OPERATION OF THE STRUCTURE:	Located upstream of the urban region to be protected, the structures hold the ice coming from the upstream reach; this occurs when the discharge increases. The pond created by the weir covers rapidly with an ice cover from the beginning of winter. This cover diminishes the frazil ice generating surface and also provides a certain storage volume for storing frazil.
STATUS:	The Ministère de l'Environnement du Québec is continuing an observation program in order to improve its knowledge of ice regimes on small rivers.
CONTACTS:	Mr. Albert-Réal Tremblay and Mr. Arthur Valcourt (Engineers) Direction des ouvrages hydrauliques, Ministère de l'Environnement du Québec 3900, rue Marly Sainte-Foy (Québec), G1X 4E4

[1]Case T303 (translated from French by S. Petryk)

TITLE: **ICE COVER COLLAPSE ON THE ST. LAWRENCE RIVER**

LOCATION: International Rapids Section of the St. Lavrence River.

BACKGROUND: Each winter the power entities endeavour to form a smooth solid ice cover through physical and procedural means, in the International Rapids Section of the St. Lavrence River to restrict the production of frazil ice and thereby maintain the channel capacity so as to carry the prescribed releases from Lake Ontario.

If river flows are too high, drag forces on the under side of the cover can cause a collapse of the cover, thus increasing head losses throughout the remainder of the winter period. Other factors also thought to affect the cover stability are wind, air, and water temperature parameters.

In the winter of 1983-84 an ice jam occurred near the ice cover formation front, lovering water levels in a section of river channel by approximately 0.3 feet. Due to increased slope of the river and drag forces, the cover in front of the jam collapsed and moved dovnstream approximately 1 km. The ice jam vas up to 25 feet in thickness.

SCOPE OF THE VORK: Ice thickness surveys are made every winter. Records exist from 1960 to date in specific sections of the river. Further data specifically about the ice cover collapse in 1984 vas collected. A videotape exists of an earlier shove that occurred in 1974.

STATUS OF WORK: Monitoring of these infrequent ice shoves vill continue to determine boundary conditions.

CONTACT:
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700 University Avenue
Toronto, Ontario
(416) 592-4475

PROGRAM: **FIELD STUDIES OF RIVER ICE JAMS AND FLOODING (Case T323)**

AGENCY: Hydraulics Division, National Water Research Institute, Burlington, Ontario.

INVESTIGATORS: S. Beltaos and J. Vong

DESCRIPTION: Annual documentations of ice freeze-up and break-up of the lower Thames River and upper Grand River in southern Ontario. The program was initiated in 1979.

GOALS:

- To develop an index for forecasting the onset of break-up.
- To identify channel features conducive to ice jamming and assess associated frequencies.
- To provide a data base for statistical analysis of peak break-up stages.
- To obtain quantitative data for testing and improving existing ice jam theories.
- To improve qualitative understanding of ice jamming phenomena as a means of guiding laboratory and theoretical research.

REPORTS:

Beltaos, S., 1981. Ice freeze-up and breakup in the lower Thames River: 1979-80 observations. NWRI unpublished report, National Water Research Institute, Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario, 67 pp.

Beltaos, S., 1983. Ice freezeup and breakup in the lower Thames River: 1980-81 observations. NWRI unpublished report, National Water Research Institute, Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario, February, 83 pp.

Vong, J. and S. Beltaos, 1983. Ice freezeup and breakup observations in the Upper Grand River: 1980-81 and 1981-82 observations. NWRI unpublished report, National Water Research Institute, Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario, May, 53 pp.

Beltaos, S., 1983. Initiation of river ice breakup. Proceedings, 4th Northern Research Basin Symposium Workshop, Norvegian National Committee for Hydrology, Report No.12, Oslo, 163-177

Beltaos, S., 1983. Ice jams. Proceedings, Conference on Frontiers in Hydraulic Engineering, H.T. Shen (Editor), New York, 230-235

Beltaos, S., 1983. River ice jams: theory, case studies, and applications. Journal of Hydraulic Engineering, American Society of Civil Engineers, 109(10), 1338-1359

Beltaos, S., 1984. A Conceptual Model of River Ice Breakup. Canadian Journal of Civil Engineering, 11(3), 516-529

SUBMISSION:

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Ph. (416) 336-4898

TITLE: ICE JAMS ON THE LAMOILLE RIVER IN HARDWICK, VERMONT

LOCATION: Lamoille River in Hardwick, Vermont

SCOPE: Thick accumulations of frazil ice (1.2 - 2.4 m) develop in the backvater behind a small dam and during break-up the ice run cannot push its way through the consolidated freeze-up cover and consequently goes over bank into the flood plain creating flooding of residential and business property.

STATUS: Several freeze-up and break-up ice control measures have been constructed by the town to minimize the flooding. These have included flood-plain improvements for water and ice conveyance, off channel storage of ice, in-stream tire booms to hold back ice and divert water into the flood plain and operational control of the small dam to pass frazil ice during freeze-up.

REFERENCES: Calkins, D.J., 1986. Ice jam flood prevention measures - Lamoille River at Hardwick, Vermont, U.S.A. Proceedings, 2nd International Conference on the Hydraulics of Floods and Flood Control, 24-26 September 1986, Cranfield, Bedford, U.K., 149-168

CONTACT: D.J. Calkins
USACRREL
72 Lyme Road
Hanover, NH 03755-1290

Ph. (603) 646-4325

TITLE: **DEVELOPMENT OF A COMPREHENSIVE NUMERICAL RIVER ICE MODEL**

BACKGROUND OF PROJECT: The NRCC Sub-Committee on the Hydraulics of Ice Covered Rivers formed the "Task Force on Numerical Modelling of River Ice Conditions" at its June 18, 1986 meeting. Following the first meeting of the Task Force, it became evident that there was an urgent need to develop a comprehensive non-proprietary numerical model, and that this model development was feasible from technical, financial and administrative points of view.

As a result a Joint Venture Consultants (Tecsult, Acres, Lasalle Hydraulics Laboratory, and MacLaren PlanSearch (Lavalin) have formulated an unsolicited proposal for the development of non-proprietary numerical river ice model. They were assisted by the Task Force.

The following two sections describe the scope of the proposed model and the methodology adopted by the Project Group for carrying out the proposed work.

SCOPE OF WORK: The proposed numerical river ice model would be designed to simulate the complex phenomena of water cooling, ice generation, transport, ice cover formation, thickening, shoving, eroding, melting and break-up. The model would be principally based on existing state of the art knowledge on river ice. In addition every effort will be made to introduce important new concepts. For example, important work is foreseen on the modelling of ice conditions subject to hydraulic transients, even though this has rarely been tried before on engineering projects. The modelling of these transients is required for the proper evaluation of hydraulic conditions and corresponding effects on the ice cover.

The model will be composed of semi-independent modules, i.e. the use will have the option of using all the modules of the model or only certain modules required for the simulation of the particular conditions being studied.

A preliminary list of modules with their functions is presented below to illustrate the planned simulation capabilities and requirements of the model.

1) Input data system.
2) Hydraulic Modelling Module. This module would carry out the hydraulic calculations while interacting with the ice regime modules mentioned below. It will mainly consist of a time varied flow model which would be capable of calculating steady state conditions, as well as calculating an ice regime which is subject or transient flow conditions. These transients are typically caused by operation of hydraulics work and/or break-up of ice covers and the subsequent relatively rapid formation/release of ice jams. The model would be quasi-two-dimensional, being able to predict the average velocity distribution across the channels (with the composite section method). Flow around islands and grounding of ice jams will be included.

   A significant research and development effort will be undertaken to determine the feasibility of modelling hydraulic surges from break-up of solid ice covers, from sudden release of ice jams and from certain peaking power plants. If feasible, a separate surge module will be included in the model.
3) Heat balance in a river reach:
   a) water-atmosphere
   b) ice-atmosphere
   c) water-ice cover
   d) other sources - tributaries
                    - power plants
   e) lateral dispersion of heat
4) Border ice - growth
              - destruction
5) Open water ice generation - frazil
                             - floating ice covers
                             - anchor ice
6) Ice transport balance
7) Initiation of ice cover
   - bridging of river (surface concentration effects, etc.)
   - geomorphic effects - islands
                        - bends
                        - spatial changes in bathymetry laterally and longitudinally along the channel)

8) Ice cover progression and thickness changes
   - juxtaposition
   - crushing
   - freezing and melting of ice covers
   - thickening and erosion by transport of ice particles
   - melting

9) Ice cover break-up:
   - accumulation covers
   - hanging dam
   - static ice covers

10) Ice cover strength
   - accumulation cover
   - cohesion effects
   - static ice cover
   - effects of water level fluctuations, rise in water level, solar radiation, degree-days of melting

11) Output data system
   - variables
   - tables
   - graphic
   - report generator type of output, designed for direct insertion simulated results in engineering reports

At the end of the proposed project, a non-proprietary numerical river ice model would be available and would be used by a relatively large number of users. This will encourage its application on a large number of rivers and will provide a common forum for exchange of future modelling experience. In turn, this should help to encourage further improvements in our numerical modelling capabilities.

PROJECT GROUP: The model development project will be carried out by a Project Group consisting of the Joint Venture of Consultants working with a relatively large number of in-house participants. The Joint Venture will be primarily responsible for designing, testing and documenting the model and the simulation results obtained from several Canadian rivers. The Inland Waters/Lands Directorate (WPMB and NWRI) will handle the programming, and help in the testing and documentation. The main in-house participants, furnishing field data and providing numerical modelling and river ice expertise related to their particular experiences, will include 12 agencies as follows: IWLD, B.C. Hydro, Manitoba Hydro, Ontario Hydro, New York Power Authority, Hydro-Québec, Alberta Environment, Ministère de l'Environnement du Québec, Ontario Ministry of Natural Resources, N.B. Department of Municipal Affairs and Environment, Department of Fisheries and Oceans and U.S. Cold

Regions Research and Engineering Laboratory. The Alberta Research Council, Trans Alta Utilities and the Government of Northwest Territories (Department of Public Works) have offered interesting river ice data for this project. Finally, the NRCC Sub-Committee on the Hydraulics of Ice-Covered Rivers will function in an advisory role and maintain liaison between the Project Group and a relatively large number of Corresponding Members. (A corresponding Member is a person who has ice expertise, is interested in the proposed model, and should provide valuable feedback to the Project Group and Sponsors).

PROJECT STATUS: This project is expected to start at the beginning of 1988.

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